博士論文

Doctoral Thesis

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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ABSTRACT

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 plants (WWTP) through struvite precipitation and sludge ash leaching processes. Currently, there are five full-scaled P recovery facilities in Japan since the first operation in 1997. However, producing recycled P costs more than the conventional mineral P fertilizers. 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 impact that would otherwise cause by the untreated WWTP's effluent, and the social impact that is embedded in the upstream resource acquisition processes. Recent publications have identified such issues as the key concerns for sustainable P production and 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 and social impacts of P fertilizers consumption in Japan from a 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 with conventional mineral P acquisition, an LCA was conducted. The author examined 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. 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 and Gifu City, respectively, and interviews with 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). An attributional LCA (ALCA) was conducted to

compare the four fertilizers. In addition, a consequential LCA (CLCA) to address the subsequent effects of MAP production was conducted. For example, by implementing the MAP process, the conventional treatment of P removal in WWTP, which was necessary to meet the local wastewater standards, can be replaced, and thus saving chemical inputs.

The ALCA results showed that mineral P outperformed recycled P in environmental performance. However, with CLCA consideration, MAP, a recycled P, was the lowest in greenhouse gases (GHGs) emission and eutrophication potential. To interpret the results, the environmental impacts were translated into monetary unit based on LIME 2 damage and weighting factors. The results showed that, by replacing one kg of FP with MAP, 55.6 JPY can be saved. However, such environmental cost is in practice not being paid. In short, for environmental performance, MAP production is preferable, depending on the technological choices and the local wastewater treatment standards.

Next, a 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 SLCA Guidelines, and improvements were made to better describe the case of P fertilizers.

A Type 1 SLCA, or 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 the 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 literature 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 overall social impacts. The social hotspots activities were identified as 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 changing to recycled P consumption, farmers in Japan could reduce the social impacts that are inherent to 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 realistically substituted. Therefore, even if the P recycling was mandate, the effects of social impacts mitigation from P fertilizers consumption at the nation scale would not be significant.

As SLCA is a young methodology, a state-of-the-art review was conducted to show the key methodological considerations such as characterization and weighting issues for different social indicators. The SLCA in this study advanced the methodology in the following research gaps: 1) limited thematic coverage in P study, 2) lack of industry-specific indicators, 3) lack of multiple life cycle phases, stakeholders, and impact categories consideration, and 4) linking functional unit to impact assessment in Type 1 SLCA.

In conclusion, this research addressed the challenges in evaluating the sustainability of mineral and recycled P fertilizers by proposing systematic frameworks based on life cycle thinking, i.e. LCA and SLCA. Recycled P is a favorable option supported by the environmental and social impact analysis. The quantitative results could facilitate future debate on the inclusion of environmental and social externalities in P recycling policy making in Japan.

Abbreviations

ALCA: Attributional-LCA

CLCA: Consequential-LCA

CSS: Country-specific sectors

FP: Fused phosphate

GWP: Global warming potential

HAP: Hydroxyapatite

IOA: Input-output analysis

EIOA: Environmental input-output analysis

LCA: Life cycle assessment

LCC: Life cycle costing

LCSA: Life cycle sustainability assessment

MAP: Magnesium ammonium phosphate, or struvite

NORM: Naturally occurring radioactive materials

P: Phosphorus

SHDB: Social Hotspots Database

SLCA: Social Life Cycle Assessment

SSP: Single super phosphate

UNEP-SETAC: United Nations Environment Programme & Society of Environmental Toxicology and Chemistry

WWTP: Wastewater treatment plants

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I dedicate this thesis to my dearest parents.

1. INTRODUCTION

1.1. Background

Phosphorus (P) recovery and recycling technologies in wastewater treatment plants (WWTP) have been advancing rapidly in recent decades [1]. The technologies were initially developed to control effluent discharging of P into water bodies. Microbiological treatments and chemical coagulations were applied to remove P in wastewater[2, 3]. The resulted P rich sediments were then landfilled or incinerated. A problem for this solution was the worsening of pipe clogging in facilities, which was caused by the unintended P precipitation in the filtrate transfer process [4]. Struvite (or Magnesium Ammonium Phosphate, MAP) precipitation was later developed to lower the P concentration in filtrate [5]. It is an add-on process to existing WWTP facilities. Chemicals, like magnesium chloride or magnesium hydroxide, are applied to form MAP crystals. MAP is collected from the reactor as a tradable recycled P by-product. In addition, another way to recover P is through the extraction from incinerated sludge ash [6, 7]. P can be extracted by adding calcium hydroxide solution under alkaline condition to acquire hydroxyapatite (HAP), a form of P. Both MAP and HAP can be sold to fertilizer producers as alternative sources to P rocks. The P fertilizers are often packed with a balance of nitrogen and potassium nutrients before retailing to farmers.

Government policies for promoting P recycling technologies have been urged to accelerate the growth of the industry [8, 9], especially after the 2008 crisis, in which the global price of P rocks spiked to eight times high their world price [10, 11]. During the crisis, Japanese fertilizer producers and farmers suffered because they were heavily reliant on imported P rocks [12]. Subsequently, the Phosphorus Recycling Promotion Council was formed [9]. The council is a collaboration between academic researchers and industry players to advocate P recycling in Japan. In fact, before the formation of the council, full-scale MAP recycling plants had been implemented in Fukuoka since 1997 and in Matsue City since 1998. The original purpose was to prevent eutrophication in Hakata Bay and Lake Shinjiko respectively. Each plant is producing 100 – 150 tones MAP annually at present [13]. In addition, HAP recycling plants had been implemented in Gifu City since 2008 and in Tottori City since 2013. The motivation for Gifu City was to save cost as producing HAP was cheaper than making recycled bricks, which was the previous waste treatment option. Tottori City was incentivized to implement P recycling in order to obtain extra subsidies for their WWTP from central government [13].

Despite the lack of local P mineral resource and the decades long efforts in technology development, P recycling is not widely implemented in Japan. Only less than 1% of the total P in the sewage system is recovered. Government and industry are reluctant to invest in P recycling because the production cost of recycled P fertilizer is much more expensive than the import of mineral P fertilizer [12, 14]. The reasons for this are the initial infrastructure cost and the maintenance cost [13, 15]. According to the latest case in Kobe City, the sales of recycled P product, MAP, could only recover chemical costs during the operation phase. However, policymakers must not decide investing in P recycling solely based on the production cost. Instead, externalities, i.e. environmental and social cost, of P fertilizers production/ consumption should be considered. Production of mineral and recycled P fertilizers can cause environmental impacts, such as global warming and eutrophication [16]. Import of P rocks to Japan, for example, involves long distance transportation that will likely lead to a higher greenhouse gases emissions. Furthermore, recycling P with MAP technology can simultaneously mitigate the algal bloom problem by reducing nutrient effluents. Also, the supply of foreign mineral P involves a high risk of social impacts. Therefore, to better support policymakers, a comprehensive sustainability assessment framework that addresses the environmental and social performances of implementing P recycling technologies is needed.

1.2. Relevant issues, concepts and research motivation

Sustainability assessment is a measure of the performance of a product, technology, or policy towards a sustainable development goal [17]. The definition of sustainable development may vary depending on different subjects of interest. A generally agreeable approach to characterize sustainable development is the Triple Bottom Line, or the People, Planet, and Prosperity—declared in the World

Summit on Sustainable Development in Johannesburg, 2002. Accordingly, people represents society, planet represents the environment, and prosperity represents the economy. The concept depicts an ideal development model for humanity, which respects geophysical constraints and social justice, equality, and so on.

Then, what defines the sustainability of P production and consumption? The answer is easier to understand from the consequences of our activities. The relevant environmental and social issues associated with P were briefly reviewed in below.

1.2.1. Environmental pollution issues

The anthropogenic P cycle is transgressing its planetary boundary, a safe operating space [18, 19]. Rockstrom et al. initially set the boundary via quantifying the P mass flowing into the ocean, the key driver of massive ocean anoxic event [18, 20]. Based on historic evidences in geological time, they have capped the P fluxes at 10 times greater than the nature weathering flows, or the level before pre-industrial era [18]; the estimated boundary is 11 millions tons annual P flow, while the year 2000 level is within the limit, or 9 millions tons [18, 21]. However, the annual P flow has increased up to 14 millions tons in an updated estimation in 2015 [19]. Therefore, we are at risk of a massive ocean anoxic event.

To make the situation worse, such global scale setting does not take regional impact such as coastal dead zones and freshwater eutrophication into account [22, 23]. In reality, one immediate treat is the possibility of regional-scale marine ecological dead zones. Marine dead zones have been spreading exponentially since 1960s, affecting 400 systems and 245,000 km^2 [22]. In response, the updated estimation of planetary boundary include regional consideration based on Carpenter's model [23]. It estimates the carrying capacity of P in freshwater to avoid eutrophication, a nutrient induced algae bloom phenomenon.

On one hand, agricultural P is the most influential non-point source of P pollution in freshwater system. Steffen et al. assumed the P fertilizer applied to erodible soil or all croplands as the P flow, and produced a spatial indicator showing the status of P in each region [19]. Such quantifying attempts at environmental ceiling of P was a rough estimation, by not accounting on factors such as crop uptake, soil retention, and erosion. Despite these short comings, the approach can be useful for promoting local adaptive measures when facing with a complex system [24]. On the other hand, untreated P from municipal wastewater is an important point source of pollution [25]. P can be removed or recovered from the WWTP. However, conventional wastewater treatment does not mandate the treatment of P due to cost concerns and a lack of sensitivity to eutrophication problems.

1.2.2. Social issues

Several social issues associated with the life cycle of P fertilizers have been identified, and some have been described as the "hidden cost" in recent literature [11].

- Human rights: Not all P is mined rightfully. Morocco, the largest of the P reserve countries, for example, is illegally occupying Western Sahara to acquire a large deposit of high-quality P ores [11, 26]. Consequently, the indigenous Saharawi people have been forced out and resettled in the refugee camps in Algeria [27].
- Health and safety: P contains naturally occurring radioactive materials (NORM) [28, 29]. NORMs are especially concentrated in the by-product or waste of the fertilizer production [30]. A lack of effective waste management and monitoring system poses radioactive health risks to communities [31, 32].
- Livelihood: P price fluctuation in international markets affects the farmers' livelihoods. In 2008, the P rock price spiked to as high as 800%, according to the World Bank [11]. As a result, extreme cases such as farmers' riot and even suiciding events were reported [11].
- Resource security: As P mineral supply is concentrated in only a few countries, the P import-dependent countries are vulnerable to the foreign policy of producers. In the 2008 event, the global P supply was disrupted due to the sudden tariff increase of P rock export imposed by the Chinese Government [11].

- Sustainability: Nykvist et al. and FAO statistics showed that countries around the world vary greatly in the use of P in term of per capita and in hectare farmland input [33]. Considering the finiteness of P, humanity is risking the long-term availability of the resource, and the equal rights to access P for the less advantageous communities.

From the above-mentioned issues, environmental and social problems of P occur in various stages of the supply chain. They are fragmented and seem to be individual events, but collectively their impacts are not to be ignored. Therefore, a systematic inquiry into the activities is crucial to evaluate the sustainability of P.

1.2.3. Life cycle assessment for system analysis

Life cycle assessment (LCA) is a field of study that systematically analyze the environmental impact performance of a product or service from a cradle-to-grave perspective. LCA investigates the input of materials in each production stage, and evaluates their potential environmental impacts. By aggregating the impacts, a complete understanding of the performance of a product or service can be realized. Therefore, LCA is useful for decision-making support when two or more options are available. More details of the framework are discussed in Section 2.1.

For recycled P, the life cycle of P fertilizer intersects with the life cycle of wastewater treatment service, particularly in the case of MAP. P is treated as an environmental flow that contribute to eutrophication from the perspective of wastewater treatment. But, P is instead treated as an economic flow that can serve as a resource. Therefore, to address the dual functions of recycled P production, a consequential-LCA (CLCA) framework is needed. Linderholm et al. investigated the production of alternative P fertilizers in Sweden. Although they tried to show consequential effects by accounting for the avoided processes in the case study, no general framework was proposed [16].

For mineral P, Silva et al. investigated the stages of mining and concentration of phosphate rock, elemental sulfur extraction, production of sulfuric acid, and manufacture of SSP in Brazil [34]. They showed that GWP and eutrophication potential were most significant in relation to eight environmental impact categories. Transportation contributed the most to GWP, and loses in SSP manufacture process contributed the most to eutrophication.

Social life cycle assessment (SLCA) is a methodology derived from LCA. Instead of focusing on the environmental flow of production process, SLCA looks into potential social impacts on stakeholders associated with the process. The social impacts evaluated in SLCA can be categorized as descriptive general, which is based on universal values, and descriptive specific, which is based on industry specific concerns [35]. Although the concept of SLCA is well established, SLCA is a young methodology that requires further study. Case studies for SLCA are limited [36]. Martinez-Blanco et al. presented a case study of compost and mineral fertilizers [37]. They showed the limitation of detailed social analysis due to the constraints of data availability.

In recent development, the concept of life cycle sustainability assessment (LCSA) has been proposed as an integration of LCA, SLCA, and life cycle costing [38, 39]. Utilizing the strength of comprehensiveness in life cycle approach, LCSA has the potential to answer bigger and more pressing concern in decision making. However, the concept is rather premature at the moment. Guinee et al. proposed a general framework to clarify the scope of LCSA [40] by broadening the object of analysis and the scope of indicators.

1.3. Aim and objectives of the thesis

In light of the research background mentioned above, this thesis was initiated to provide an improvement to the existing methodology based on the life cycle approach. Particularly, the work tried to fill in the research gaps of lacking a generalizable LCA framework that addresses the multi-functionality of P recycling technology, and lacking an operational SLCA framework that is specific to the P industry.

The overall aim of this thesis was therefore to develop and examine comprehensive frameworks to compare the environmental and social impacts of mineral and recycled P fertilizers. The work intended to support P recycling policy in Japan. By contrasting the "sustainability" performances of mineral and recycled P with scientific data, a better decision could be made in order to transition to a sustainable mean of production/consumption of P fertilizers.

Deriving from the research goal, the specific objectives of the thesis were to:

1) Evaluate the environmental impacts (GWP and eutrophication potential) of fertilizers production of mineral P (SSP and FP) and recycled P (MAP and HAP) in Japan with a reusable LCA framework.
2) Evaluate the (potential) social impacts associated with the production and consumption activities of mineral and recycled P in Japan with an original P-specific SLCA framework.

According to the research objectives, this thesis was structured in eight chapters, as below.

1) Introduction: To provide an overview of problem related to promotion of P recycling technology in Japan, and the sustainability concerns of P in a global context; and to clarify the aim and objectives of the thesis.
2) Research Framework: To introduce the methodological background of LCA, SLCA and LCSA. Also, to provide a review of SLCA in recent literature.
3) Materials: To specify the study objects for Objective 1 and Objective 2. Also, to provide a background information of P flow in Japan.
4) Methods: To introduce the methodology of LCA and SLCA developed for this study.
5) Results and discussion (environmental impact): To present the LCA result and discussion for Objective 1.
6) Results and discussion (social impact): To present the SLCA result and discussion for Objective 2.
7) General discussion: To discuss the challenges of fitting LCA and SLCA into the LCSA framework. And, to suggest a future study based on a stakeholder-centered approach to supplement the lack of on-field qualitative information.
8) Conclusion: To provide a concluding remark and a review of research findings or highlights from the thesis chapters.

2. REVIEW OF EXISTING RESEARCH FRAMEWORK

This chapter introduced the methodological background of LCA, SLCA, and LCSA used in this thesis. The author focused more on the review of SLCA methodology as a main contribution of this thesis.

2.1. LCA framework for environmental impact analysis

LCA is a well-established methodology for the evaluation of environmental impacts. The earliest studies were from 1970s when broad public concern was drawn on environmental issues such as resource and energy efficiency, pollution control, and solid waste management [40]. Until the 2000s the principles and framework of LCA was standardized by the International Organization for Standardization, under the title of ISO 14040. However, divergent approaches with respects to system boundaries, and allocation method had been published to suit the purposes in different cases. In this thesis, for the environmental impact analysis, a basic ISO framework was first applied, and then an improved modeling method, CLCA was applied.

Figure 2-1 showed the LCA framework according to ISO standard. The basic four steps are to define a specific goal and scope of the study, collect and analyze the inventory data, perform impact assessment, and interpret the results. LCA is an iterative process that often requires a repetition of the four steps to refine the assessment based on a preliminary finding. The function of LCA is to help product development and improvement, strategic planning, public policy making, marketing, and others.

In LCA, practitioners investigated two type of flows, economic flow and environmental flow. Economic flow is the material flow that connects each life cycle stages. For example, P rock connects mining process to fertilizer production process based on the requirement of P rock for one unit of fertilizer. Environmental flow is the quantification of impacts exerted to the environment. Practically, to conduct a LCA, we have to collect the raw inventory data on input/output of processes related to the

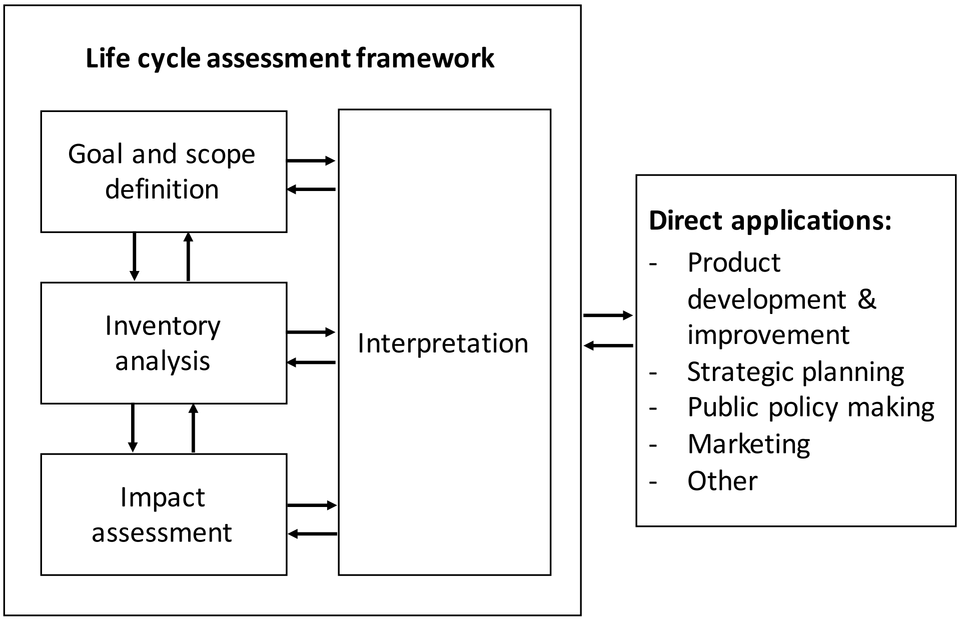

Figure 2-1. A basic LCA framework based on the ISO standard [41].

study object, or the economic flow, like electricity demand and chemical input required for one unit of fertilizer production. The inventory data is then multiplied by the emission factor to reflect the environmental flow. For example, 1 kWh of electricity use in Japan contributes to 0.554 kg-CO_2 equiv. of greenhouse gases emissions. Instead of having a direct measurement, such emission factors are usually adapted from commercially available LCA databases, such as the international database of Ecoinvent and Japanese database of IDEA.

Evaluating environmental impacts of a product based on the attribution within a chosen system is sometimes insufficient. The output of the product may change the demand of another product, and subsequently changes the environmental impacts of the wider system. Therefore, in contrast to the conventional attributional type of LCA (ALCA), the CLCA, or consequential-LCA, method was proposed to reflect a more realistic result. CLAC model estimates how environmental and economic flows within a system change in response to a change in output of the functional unit [42]. The model often utilizes the system expansion technique that attempts to include a set of linking subsystems in the scope of assessment. Thomassen et al. showed the differences of ALCA and CLCA of milk production. An increase of milk production, for example, will lead to increase demand of soybean meal, and an increase of soybean oil as a by-product, and a decrease of palm oil as a replacement of soybean oil.

Previous LCA studies have comprehensively covered the P removal technologies, but not the P recovery processes in WWTP [3, 43]. A possible reason was that full-scaled P recovery facilities were relatively scarce [14]. Linderholm et al. provided a valuable case study from Sweden. They compared the energy use and global warming potential (GWP) of P alternatives, MAP, HAP, and sludge [16]. Their results showed that MAP had lower GWP impact than mineral P. Based on that study, there was a need to clarify the consequential effects in the accounting method, and construct a reusable LCA framework for the assessment of recycled P fertilizers in general. Other P related studies included theoretical estimation of HAP environmental performance in Sweden [7, 44], and economic evaluation of MAP in global scale [45].

2.2. SLCA framework for social impact analysis

SLCA is a derivative of LCA. The concept of SLCA emerged in 1990s when LCA (applied) scientists were working together with social scientists in a multidisciplinary environment [46]. With the broad acceptance and application of LCA, it was clear that environmental impacts were not the only relevant concern for decision making. Based on two milestones in SLCA, UNEP-SETAC Guidelines for Social Life Cycle Assessment of Products (the Guidelines) and Social Hotspots Database (SHDB), a three-stage-development was observed. Before the Guidelines, most studies were focusing on constructing the theoretical concepts to define the study scope, selection of stakeholders, and category of social impacts [47-49]. In 2009, the Guidelines was published by leading SLCA scholars. They set the tone for future study by providing the key concepts, elements, and research needs. After the Guidelines, most studies shift the attention to proposing specific indicators, inventory datasets, and weighting options for different cases [50-52]. The SHDB was launched in 2009 and become publicly available in 2013. Developed by the New Earth, SHDB collected the inventory data on impacts of global supply chain based on reputable third-party reports and literature, and characterized the social risks accordingly. SHDB eased the intensive data collection process. As a result, after the SHDB, more and more streamlined SLCA case studies were produced [37, 53].

SLCA assesses the social and socio-economic aspects of products and their potential impacts along their life cycle to improve the well-being of the stakeholders [46]. A SLCA framework essentially follows the four-steps LCA framework—goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. However, due to the nature of social impacts, the assessment system is different. Figure 2-2 shows the assessment system of SLCA based on the Guidelines. In addition to depicting the processes or life cycle stages of a product, stakeholders' categories and social impact must be defined. Unlike the environmental LCA, SLCA does not have solid (nature) scientific based indicators or measurement to characterize the impacts. Therefore, subcategories and social indicators have to be designed based on the context of the study object.

Nowadays, the concept of SLCA is generally agreeable among the LCA community, but the methodology is still young. A growing amount of SLCA studies on theoretical discussion and case studies were published in recent years to advance the methodology [36, 54-57].

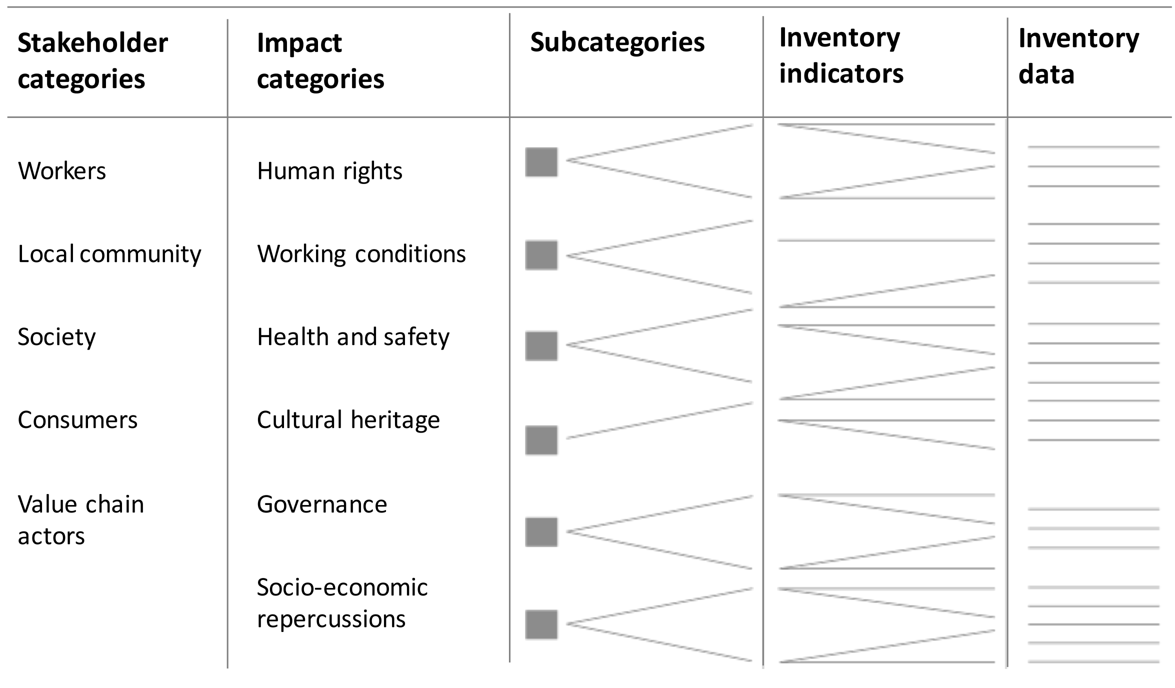

Figure 2-2. An assessment system of SLCA based on the UNEP-SETAC's Guidelines [46].

2.2.1. Review of SLCA in recent literature

In the light of growing interest of SLCA and the diversity of recent SLCA publications, there is a need to review the latest methodology development. Based on recent SLCA review articles—Garrido et al. (2016)[58], Chhipi-Shrestha et al. (2015)[55], Wu et al. (2014) [36], Parent et al. (2013)[59], Jorgensen (2013)[60]—I conceptualized the SLCA framework, and pointed out the key concerns in the methodology. Showing in Figure 2-3, the SLCA framework was structured based on the 4-steps-LCA-framework in ISO 14040 [41].

In addition, to gauge the state-of-the-art of SLCA, the author reviewed eight recent SLCA case study articles, published in between 2015 to 2017, from International Journal of Life Cycle Assessment and Journal of Cleaner Production. These case studies showed the actual progress of the methodology development when applying to realistic environment.

Goal and scope definition

The methodological approach for SLCA was greatly depends on the goal and scope of the assessment. Table 2-1 summarized the goal and scope of the recent eight SLCA article, in term of object of study, purpose, functional unit (FU), and system boundary.

Purpose

Due to the infancy of the methodology, most of the recent articles were aiming to explore the application challenges of SLCA methodology instead of providing a concrete decision support [61, 62]. Nevertheless, Wu et al. summarized the three common purposes of SLCA: overall decision support, hotspots identification, and alternative comparisons [36].

- Overall decision support, was a stand-alone assessment that aimed to evaluate the potential social impacts of introducing a product or a service. An example was, Dong et al. study on building construction project in Hong Kong, which the purpose was to evaluate the social impacts related to the construction. The finding showed on-site environmentally friendly practices would simultaneously generate social benefits, and adoption of precast concrete components would reduce local employment and thus the impacts was depending on the supply of labor workforce [63].

- Hotspots identification, was aimed to identify the unit processes that exerted the most negative social impact; or to identify the social impact categories that were most severely impacted in a product/service life cycle. An example was, Wang et al. study on IC packaging company, which the objective was to identify potential improvement of labor practices. Through SLCA of three companies, they found that "lacking labor union", "did not hire a sufficient number of disabled employees", "overtime work that exceeded the legal limit", and "excessive number of dispatched workers" were the most critical social impacts related to the industry.
- Alternative comparison, was aimed to compare the social performances of A to B or more products/services. These types of studies were to contrast the relative performance of given options. A direct comparison of two products with identical FU was difficult because they would have similar unit processes that could not distinguish based on current SLCA databases (which were mainly providing data at sector-level). An example was, Sousa-Zomer et al. study on a water filter leasing service versus a reverse osmosis water filter service. They could not complete the comparative SLCA due to the data constraint [61]. Alternatively, a comparison could be performed based on two scenarios—prospective scenario as a result of the introduction of a technology, and a reference (existing) scenario. For example, Van Haaster et al. were able to evaluate the prospective social impact, e.g. total employment change, by introducing carbon capture and storage technology in coal-fired power plants [62].

In addition, Jorgensen et al. defined the purpose of SLCA for based on three hypothetical effects of SLCA in improving the social condition of stakeholders—consequential SLCA, educative SLCA, and lead firm SLCA [64]. Consequential and educative SLCA support the decision of choice between products/components or services, or similar to the purpose of "alternative comparison". The differences were consequential SLCA asked "what are the social impacts caused by decision alternative A, B...?", and aimed to alter the production processes in one company; educative SLCA asked "how is A, B... performing in relation to a defined code?", and aimed to educate the market to choose an option that had a better social performance (score)[64]. Lead firm SLCA was closer to "hotspots identification", in which company was looking into the priority of conduct changes that would improve the impacts on workers. However, such definition of purpose was only applicable to a company-level assessment, other scope of study such as economic-wide-level for policy support was not applicable.

Functional Unit

A FU is necessary to specify the function of a study object and to provide a reference to which all related inputs and outputs in LCA [46]. Although defining FU was a standard practice in LCA as defined by ISO 14040, this was not the case for SLCA study [55]. Chhipi-Shrestha et al. showed that 3 out of 11 of the case studies (Type I SLCA), which they reviewed, did not specified the FU [55]. Wu et al. argued that in contrast to environmental impact in LCA where FU was a basic quantitative measure of each unit process unit (that applied to quantify the inventory data), social impact in SLCA were based on the behaviors of a company, industry, or country, therefore could not be linked by the conventional sense of FU [36]. However, there were some studies (Type II SLCA) that were able to more conveniently apply a consistent definition of FU as LCA (see further discussion of Type I and Type II SCLA in impact assessment section).

From a practitioner point of view, Garrido et al. classified the FU based on the scalability of FU with the inventory indicators [58].

- A scalable FU must be quantitative. For example, an indicator of local employment could be measured as "person multiple hours of work required for a product FU" [58]; and the relationship of the indicator and FU could be scale linearly.
- A non-scalable FU were mostly a description of an overall performance of a company [65], a production process [66], or a scenario of technology introduction [62]. The resulted social impacts were often not able to specify the differences in relation to the changes in FU. For example, the SLCA assessment would not be able to show how much social impact could be mitigated if the use of soap was reduced by half in Ramirez et al. study.

From my selected case studies, only three out of eight specified the FU; all of them were non-scalable, except one from Van Haaster et al., which was scalable for their quantitative indicators but not the qualitative indicators [62]. See Table 2-1 for the full list of FU in each study.

System Boundary

System boundary of SLCA comprised of the declaration of life cycle phases (unit processes), stakeholder's categories, and social impact categories, considered in an assessment. In LCA, life cycle phases commonly described as cradle-to-grave, cradle-to-gate, or other phrases to specify the interests of study; a broader scope was achievable as the environmental impact categories were characterized universally in the full life cycle stages. In SLCA, social impacts were more heterogeneous in different life cycle stages. For example, social issues in a raw material mining process, was not the same as a fertilizer manufacture process.

To better define the system boundary, an identification of stakeholders and its related social impact categories were necessary. The Guidelines recommended five common stakeholders: worker, consumer, local community, society, and value chain actors [46]. The stakeholder's categories were paired with 33 suggested generic social impact categories, such as freedom of association and collective bargaining, child labor, health and safety, respect of indigenous rights, and public commitment to sustainability issues [46]. Practitioners were also encouraged to propose specific stakeholder-impact categories for designated theme of study. However, it was neither practical nor mandate to evaluate all of the stakeholder-impact categories due to the extensive scale of investigation. A selection of representative stakeholder-impact categories for a study were often conducted prior to the inventory.

An expansion of life cycle phases in a study would significantly increase the associated stakeholder-impact categories. And, the resulted social impacts assessment would become harder to converge into a simple aggregated interpretation. Therefore, in reality, most SLCA case studies were simplified to have a limited steps of life cycle phases, and stakeholder-impact categories. For example, Wang et al. considered a single factory phase, and impacts on worker category only [65]; Van Haaster et al. considered the overall production and consumption phases without specifying the unit processes, and assessed six quantitative and four qualitative indicators [62]; Arcese et al. proposed to consider three phases of wine production, and five stakeholder categories with more than 50 impact categories, without actually conducting the inventory [67]. See Table 2-1 for full list of system boundary description of the selected case studies.

Life cycle inventory analysis

Life cycle inventory analysis was a process to collect data on unit processes and social impact indicators [46]. Based on the function of inventory data in modelling, inventory related to input-output of unit processes was known as economic flow (e.g., x amount of electricity to produce y amount of product), while the inventory related to impacts was known as environmental flow (process a causes b amount of impact). The discussion on economic flow inventory was excluded since SLCA case studies with scalable functional unit was less studied, and in most cases, they were similar to environmental LCA. The author summarized the environmental flow analysis of the selected case studies in Table 2-2.

Data collection

Wu et al. classified the data collection for SLCA as site specific and desktop search [36]. Site specific data collection involved questionnaire survey to relevant stakeholders, and interview with experts and key stakeholders. Desktop search involved manually collecting statistic data from each authority, or collecting data through third party databases such as SHDB. These data collection approaches had their pros and cons:

- Site specific data collection
    - Provide a large amount of original data to compensate the lack of on-site understanding of specific social issues [62].
    - Provide reference of weighting different social impacts based on subjective judgement and opinion of stakeholders [68].
    - Collected data were specific to the case study (e.g. performance of one company) and not transferable to other related study [65].

- Collected data were subjected to the bias of stakeholders' motivation, interest, and knowledge [68].

- Desktop search
  - Access to a vast collection of data on universally concerned social indicators from company reports, government authorities, international organizations, and third party databases [61].
  - Reputable databases provided a quantitative and standardized dataset that was replicable to other case studies [61, 62].
  - Most available data were at country level that were insufficient to depict the detailed unit processes and industry-specific concerns [55].
  - detailed unit processes and industry-specific concerns [55].

Data level

Data level or resolution of the available data was one of the biggest constraint in conducting a detailed SLCA [36]. In general, data level could be categorized as unit process, company, industry/sector, and country. From a top-down perspective, global data for indicating social and socio-economic issue were vastly collected by international organization such as the United Nations and the World Bank based on country level. Downscaling the data to sectoral level might not be feasible. Therefore, desktop search approach had it limitation in interpretation [46]. From a bottom-up perspective, unit process and company level types of data could be collected through questionnaire and survey. This was a convenient way to generate data; however, as mentioned before, these data were subjected to bias and not transferable to other cases.

Characterization of Data

Data indicators for social impact were mostly an indirect measurement or a proxy to the interested social impact. In most cases, data characterization was conducted during the inventory process to communicate the implication of the collected data [58]. For example, SHDB databases would provide an indication of a social risk levels—low, medium, high, or very high risk—to each of the inventory data. To make the characterization explicit, Garrido et al. summarized some of the common approaches.

- Based on norms and best practices—This type of assessment was most widely used and closer to the original definition in the Guidelines [58]. Typically, the assessment performed with a selected level of scale, correspond to the level of compliance with international norms or industry-specific best practices. For example, Wang et al. characterized the performance of worker-related indicators by surveying whether a factory fully, partially, or not implemented a selection of activities that were meant to protect the labor rights [65]. Agyekum et al. characterized the respect of indigenous people rights based on binary observation of "whether permission for using local bamboo resources was acquired" and "awareness of resource owner prior to pricing" [66].
- Based on geographical context—This type of assessment acknowledged the local norms and socio-economic standards based on geographical context [58]. Standard for characterizing excessive working time hours, for example, might be different based on the average working hour in a society. None of the selected case studies took this approach as the inventory process would be more intense depending on the sites (countries) involved.
- Based on stakeholders' or experts' judgement—Subjective judgement was acceptable and sometimes encouraged as an input to SCLA due to the heterogeneous nature of social impacts [46, 58]. For example, Ramirez et al. used the supplier satisfaction surveys of Natura company to characterize working condition related to their value chain actors [69]. Fan et al. collect and characterize data from the stakeholders by questionnaire, in which stakeholders were asked to judge the level of conformity of each activity in green building construction [70].
- Based on researchers' judgement—Researcher or LCA practitioner was able to gauge the most salient social issue in a product life cycle learning from studies and experience, therefore appropriate to characterize an inventory data when other references were absent [58].
- Based on the position in a distribution performances—This type of assessment based on how a performance was positioned with regards to a distribution of performances [58]. For example, in

SHDB, one country's data like "percent of child labor in China" was compared with the global distribution of the data. The country's data was categorized as low risk if the data fells within the first quartile of all sample. Sousa-Zomer et a. took this approach as most of the inventory data were adapted from SHDB [61].

Life cycle impact assessment

Two major types of treatment of impact categories in SLCA were developed since the recommendation of the Guidelines—Type I: performance reference point method, and Type II: Impact pathways method [36, 55]. According to the Guidelines:

- Type I SLCA

  "Impact categories used in SLCA will correspond to the goal and scope of the study and represent social issues of interest that will be expressed regarding the stakeholders affected and may cover health and safety, human right… The subcategory indicator results are aggregated into impact category results."

- Type II SLCA

  "Impact categories correspond to a model of the social impact pathways to the endpoints human capital, cultural heritage and human well-being, the latter with the midpoints health, autonomy, safety, security & tranquility, equal opportunities… For the time being, the causal models in social sciences are generally not well developed."

The main differences were the causal linkage between the inventory data (e.g. content of U-238 series, natural occurring radioactive material, in P rock) and the endpoint impact category (e.g. human health of local community in the mining area). Type II SLCA was meant to characterize such impact pathway in a quantitative manner, or model the correlation between the two with existing theory. A FU for Type II SLCA would be a scalable FU. But, Type I SLCA treated the indicators as one of the subcategories, and the level of social impact was treated independently; the endpoint impact category would be an aggregated result of the subcategories [55]. Therefore, impact assessment of Type I SLCA required less empirical evidence and knowledge, and thus more feasible in comparison to Type II SLCA.

The selected SLCA case studies were all based on Type I SLCA. To aggregate the impact categories, the two main considerations were weighting of stakeholder-impact categories, and weighting of unit processes [58]. More discussion of Type II SLCA was reviewed by Chhipi-Shrestha et al. [55].

Weighting of stakeholder-impact categories

In Type I SLCA, to show the relative importance of specific social issues, a weight must be given to all subcategories [46]. Since a stakeholder category were always paired with a certain number of impact categories, here, the term "stakeholder-impact categories" were used. The weighting methods were summarized as below based on Garrido et al. [58].

- Based on implicit equal weighting—This method assumed an equal importance of all stakeholder-impact categories, therefore avoided any preferential treatment or discrimination. In practice, many recent studies applied equal weighting implicitly as justifying an alternative weighting was troublesome and less objective [61, 66, 69]. However, some researchers might criticize that an equal weighting was also based on a strong assumption that all social issues were as important.
- Based on worse performance in a subcategory—This method would evaluate an impact category based on the worst performance among its subcategories. This was based on the idea of equal importance of all subcategories, and none of the subcategories could substitute the performance of another [58].
- Based on stakeholders'' or experts' judgement—This method weight the social issue based on the subjective opinion and preferences of stakeholders and experts. This was a favorable approach for SLCA that based on site specific data collection as additional information could be simultaneously collected [63, 65, 70].
- Based on researchers' judgement—As mentioned in data characterization method, researcher or LCA practitioner would give a weight based on other studies and experiences.

Weighting of unit processes

In environmental LCA, relative importance of unit processes was commonly treated based on an economic flow of the FU, or input-output of material in mass unit. In Type I SLCA, however, the FU was not scalable with the unit processes. Therefore, an explicit weighting was necessary. Since the unit processes in SLCA "contained" a selection of stakeholder-impact categories, sometime they were weighted together. Nevertheless, Garrido et al. showed two common weighting method. First, was based on implicit equal weighting as described in previous section. Second, was based on activity variable (or activity coefficient).

An activity variable was a variable representing a quantifiable activity that could be measured at the different unit process and scaled to a FU [58]. Technically, any variable that could scale with a FU could be treated as an activity variable. A more popular choice of activity variable was working hours—the number of working hours needed for the provision of one functional unit—because it linked well with labor rights and decent work kind of impact category. Such data was also available in Gabi database [37]. However, working hours was not applicable to other stakeholder-impact categories as they were not related to the labor input. Ekener-Peterson et al. proposed an alternative activity variable based on the contribution of unit processes in different countries of production [51]. Since most SLCA inventory indicators were based on a country level, and a product supply chain commonly involved multiple sources in different countries, such activity variable could effectively weight the unit processes.

Life cycle interpretation

The final step of SLCA was the life cycle interpretation. Interpretation consisted of the presentation of impact assessment result and the evaluation of study [46].

Depending on the goal and scope definition, and the level of result aggregation, there were three common ways to interpret a result:

- Identification of significant issues—to show social impact hotspots of an object of analysis. Hotspots were usually identified in the level of unit process or social impact indicator, which were not aggregated [61]. Therefore, subsequent actions could be proposed to improve the well-being of stakeholders.

- Aggregate in stakeholder-impact categories—to show a concise interpretation of social performance for better communication with stakeholders and decision makers. This was a popular type of presentation as it involved minimum steps of weighting of social impact indicators within the stakeholder-impact categories, and provided a balance of information without too much subjective weighting [66] [69, 70].
- Single score representation—to show a simple single score representation of social performance for the studied object, which could be useful in a direct comparison of two or more alternatives [62, 63, 65]. A drawback of such interpretation was information was highly aggregated and difficult to give meaningful detailed explanation.

Since SLCA was a young methodology, a complete assessment was not expected. The Guidelines recommended a self-evaluation in post-assessment to clarify the limitation of the study [46]. First, was the completeness to show if all the relevant critical issues had been addressed, and all necessary data collected. Second, was the consistency to show if modeling and methodological choices were appropriate for the defined goal and scope.

Research gaps and significance of study

Based on the mini-review in full aspects of SLCA, I would like to draw attention to some of the existing research gaps and how this thesis work would advance the methodology.

- Current thematic coverage of SLCA was limited although the field was rapidly growing. This was the first and only SLCA study regarding P fertilizers. The closest existing study was a Nitrogen fertilizers case conducted by Martinez-Blanco et al. [37]; and the social concerns of Nitrogen fertilizers were distinctively different to P fertilizers.
- Indicators considered in existing SLCA studies were predominantly universal social issue such as human rights as suggested by the Guidelines. To make SLCA relevant to decision making, Kruse et al. emphasized the need of specific descriptive indicators [35]. This study reviewed and proposed a set of original indicators specific to P production and consumption, and thus providing a guideline for future study.

- Case studies with a scope of multiple life cycle phases, stakeholders, and impact categories were rarely discussed using the desktop search approach. By attempting to cover a broader scope, which was crucial to P fertilizers production and consumption, this study showed the challenges of different level of weighting that would occur in a realistic situation.
- Linking FU to impact assessment in Type I SLCA was important but not discussed by many researchers. A feasible pathway was through the activity variable method. Activity variable was currently dominant by the concept of "working hours" as weighting factor, due to the conveniences of data availability provided by commercial LCA database (Gabi). However, Ekener-Peterson et al. showed that weighting factor based on material flow from different countries was also critical to SLCA [51, 53]. This study advanced the latter argument by providing an example under different context.

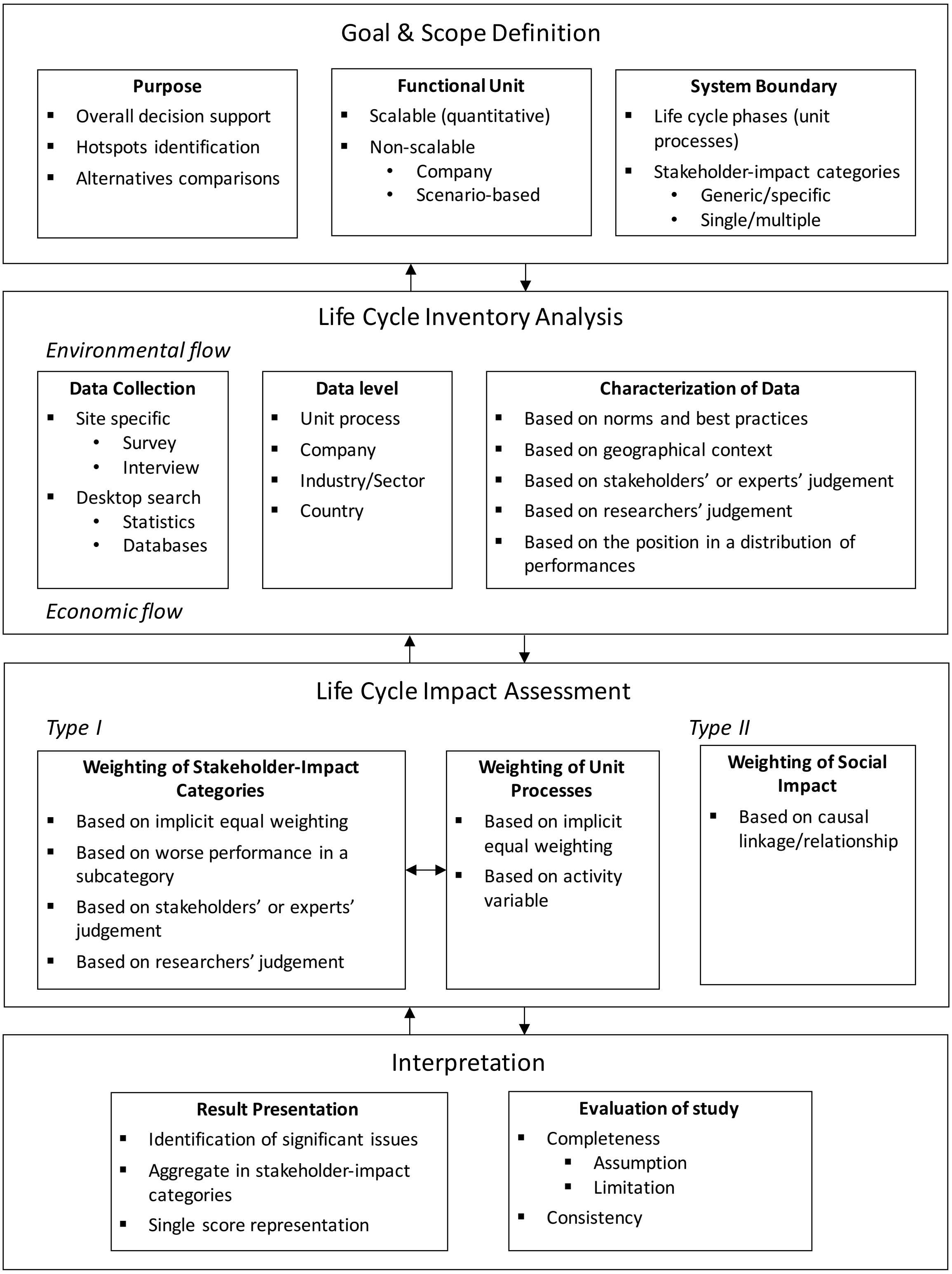

Figure 2-3. Overall framework and key considerations in SLCA.

Table 2-1. Review of goal and scope definition based on eight selected recent SLCA case studies.

	Goal and Scope Definition			
	Object of Study	**Purpose** *(P1: Overall decision support, P2: Hotspots identification, P3: Alternative comparisons)*	**Functional Unit**	**System Boundary** *(LC: Life cycle phases, S-I: Stakeholder-impact categories)*
Wang et al. (2017)[65]	IC packaging companies	P1: Demonstrate the labor impacts in the industry. P2: Identify potential improvement of labor practices.	Three IC factories in Taiwan (unspecified, non-scalable)	LC: Factory phase (single) S-I: Worker only, 19 labor-indicators (generic, based on the Guidelines).
Van Haaster et al. (2017)[62]	Carbon capture and storage technology in coal-fired power plants*	P1/P3: Show the social impacts associated with the introduction of carbon capture and storage technology	1 kWh electricity delivered to the grid (specified, partially scalable).	LC: Overall production and consumption phase (unspecified) S-I: Worker and society, 6 quantitative and 4 qualitative indicators (generic and industry-specific).
Arcese et al. (2017) [67]	Italian wine sector	P1: Identify socio-economic impact subcategories and indicators for the wine industry.	75 cl bottle of wine made 100% from glass (specified, non-scalable)	LC: Agricultural, transformation, and use phases (3 phases). S-I: Workers, local community, value chain actors, consumers, and society (5 categories, based on the Guidelines), around 50 impact subcategories**.
Agyekum et al. (2017) [66]	Bamboo bicycle frames in Ghana	P1: Determine the social and socio-economic impact of the bamboo bicycle frame production,	Three bicycle producing companies (unspecified, non-scalable).	LC: Bamboo extraction, bamboo processing, making of bamboo bicycle frame (3 phases) S-I: Workers and local community, 17 indicators (industry-specific, based on the categories in the Guidelines)

		P2: Improve the socio-economic aspects of the production		
Ramirez et al. 2016 [69]	Natura's cocoa soap	P1: Test the application of a SLCA method, subcategory assessment method.	The soap for cleaning baths of a person over 1 year, 10 cocoa soaps that weighed 150 g each.	LC: Cocoa cultivation, palm oil production and cultivation, cocoa butter/final picking, soap production, logistics (7 phases) S-I: Workers, local community, consumer, society, and other actors of value chain, 25 indicators (generic, based on the Guidelines)
Fan et al. (2016) [70]	Green residential district	P1: Evaluate the social impact of a green building district within its designed service life, 50 years	Green residential district, author claimed hard to be clearly defined (unspecified, non-scalable).	LC: Pre-construction, construction, and post-construction phases (3 phases) S-I: Local government, construction enterprises, real estate developers, and community residents. 15 indicators (industry-specific). Q
Sousa-Zomer et al. (2015) [61]	Product-service system (PSS): a water filter leasing system and a reverse osmosis water filter system.	P1: Discuss the main challenges involved in applying SLCA to PSS assessment. P3: Comparative analysis of two PSS business models and the consequences of PSS introduction into the market.	The provision of a certain amount of drinking water for a certain time, author claimed hard to be clearly defined (unspecified, non-scalable)	LC: Raw materials, product manufacturing, product distribution (3 phases) S-I: Workers, local community, consumer, and society (generic based on the Guidelines and industry-specific)
Dong et al. (2015) [63]	Building construction in Hong Kong	P1: Develop SLCA method for building construction projects	Building construction projects (unspecified, non-scalable)	LC: From cradle to end of construction (multiple phases). S-I: Workers, local community, and society, 13 indicators (generic based on the Guidelines, and industry-specific).

Table 2-2. Review of life cycle inventory analysis, impact assessment, and interpretation based on eight recent SLCA case studies.

	Life Cycle Inventory Analysis			**Life Cycle Impact Assessment (Type I)**		**Life Cycle Interpretation**
	Data Collection *(SS: Site specific, DS: Desktop search)*	**Data Level**	**Characterization of Data** *(C1: norms and best practices, C2: geographical context, C3: stakeholders' or experts' judgement, C4: researchers' judgement, C5: position in a distribution of performances)*	**Weighting of Stakeholder-Impact Categories** *(WSI1: Equal weighting, WSI2: worse performance in a subcategory, WSI3: stakeholders' or experts' judgement, WSI4: researchers' judgement)*	**Weighting of Unit Processes** **(***WUP1: Equal weighting, WUP2: based on activity coefficient)*	**Result Presentation** *(ID: Identification of significant issues, ASI: aggregate in stakeholder-impact categories, SSR: Single score representation)*
Wang et al. (2017)[65]	SS: Company reports, websites, and interview with company managers DS: Government statistic	Company level	C1: 3 level based on fully, partial or not implementation of best practices shown in the indicators.	WSI3: Based on the experts' opinion on the relative importance of the indicators	-	SSR
Van Haaster et al. (2017)[62]	SS: Representative survey (n=654) DS: Data for quantitative indicators.	Industry/sector level	No characterization and no risk level shown; show absolute differences and direction of change.	WSI1: A scenarios with same weighting for all category. WSI3: A scenario with experts' survey weighting.	WUP2: Included in stakeholder-impact categories weighting	SSR
Arcese et al. (2017) [67]	Not conducted.	-	-	-	-	-

Agyekum et al. (2017) [66]	SS: Interviews and site observation.	Unit process (excluding secondary process) and company level	C1: 5 level based on best practices of property rights, local employment etc. and based on meeting the law requirement.	WSI1: Implicit equal weighting	WUP1: Implicit equal weighting	ASI
Ramirez et al. 2016 [69]	SS: Questionnaire to related stakeholders.	Unit process (excluding secondary process)	C3: 3 level based on stakeholders' survey.	WSI1: Implicit equal weighting	WUP1: Implicit equal weighting	ASI
Fan et al. (2016) [70]	SS: Questionnaire to related stakeholders.	Unit process (excluding secondary process)	C3: 5 level based on stakeholders' survey.	WSI3: Based on stakeholders' questionnaire and experts' interview	WUP2: Included in stakeholder-impact categories weighting	ASI
Sousa-zomer et al. (2015) [61]	DS: SHDB database	Unit process	C1, C5: 4 level based on SHDB.	WSI1: Implicit equal weighting	WUP1: Implicit equal weighting	ID
Dong et al. (2015) [63]	SS: Questionnaire to related stakeholders. DS: Government statistics.	Unit process (excluding secondary process)	No characterization and no risk level shown; show absolute score.	WSI3: Based on stakeholders' questionnaire and experts' interview	WUP2: Included in stakeholder-impact categories weighting	SSR

2.3. LCSA framework for sustainability assessment

LCSA is the future of LCA [40]. In the light of growing public awareness of sustainability and advancement in sustainability science, leading LCA scientists have been advancing the LCA methodology towards LCSA to meet the current trend [71]. LCSA, for example, is a suitable tool to for measuring the performance of sustainable consumption and production of a product or a service—the 12th Sustainable Development Goal.

Guinee et al. proposed a LCSA framework that broaden the scope of LCA in two dimensions (Figure 2-4) [40]. First, was the objects of analysis. Three different levels: product, meso (national policy), and economy-wide were proposed. Conventional process-LCA is based on a product level assessment. But, often decision-making for national policy was made at an economy-wide scale, which affects multiple related products and is constrained by the national condition. An example would be, "the comparison of different options for Swedish production of biofuel to replace 25% of the fossil vehicle propellants in Sweden in the year 2030" [38]. Second, was the scope of indicators. Impacts from three different aspects: environmental, social, and economic, were supposed to be equally important, reflecting the three-bottom line of sustainability. Based on these considerations, LCSA had to address the problem of integration.

Kloepffer pointed out two options for future LCSA [39]. Option one: LCSA = LCA + LCC + SLCA, which is based on three separate LCA with consistent system boundaries. Option two: LCSA = "LCA new", which is based on a highly-integrated set of inventories for sustainability. However, Finkbeiner et al. and Sala et al. showed that one of the main challenges of LCSA was the incompleteness of current SLCA methodology to support the desired assessment [71, 72]. Currently, there are no case study that addressed the above-mentioned issue.

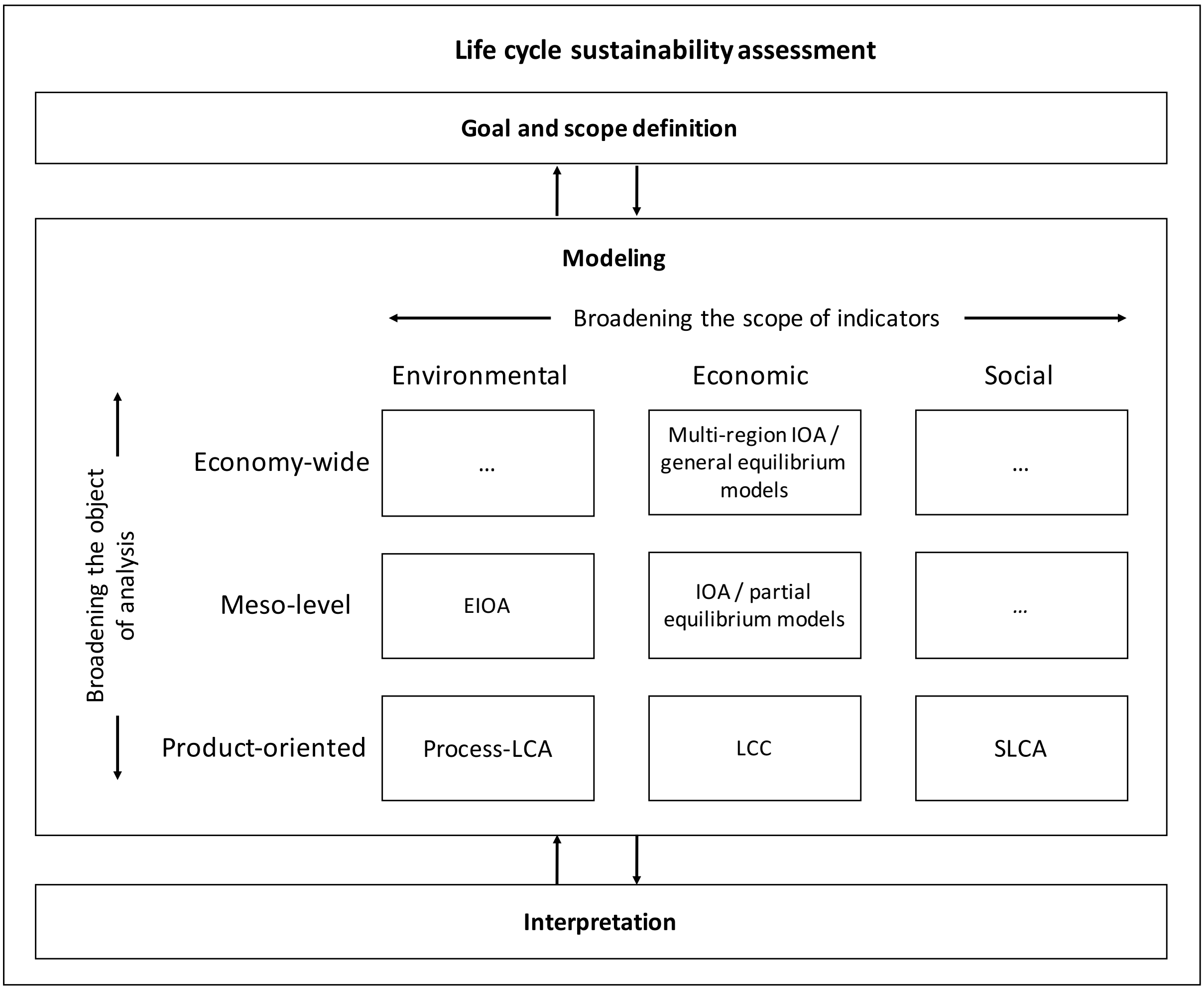

Figure 2-4. A framework for LCSA adopted from Guinee et al. work [40].

3. MATERIALS

This chapter described the study objects of the thesis, and provide a background of P flow in Japan.

3.1. Overview of study objects

Even though the terms “mineral P” and “recycled P” were used throughout the thesis, their context were slightly different for the two parts of the analysis. Based on the LCSA framework [40], the scale of analyzed objects was categorized. The author mapped the objects of analysis in Figure 3-1.

For Objective 1, a product-oriented environmental LCA was conducted. The main factor for environmental performance were technological choices. Therefore, the distinction between the variety of P fertilizers matter. Mineral P fertilizers were represented by SSP and FP (see page vi for all abbreviations), and recycled P fertilizers were represented by MAP and HAP. The study objects were the production of the four fertilizers.

For Objective 2, a meso-level (or national level) social LCA was conducted. The factors used to assess social performance were the practices in one sector or one country. Therefore, the sources of P fertilizers in Japan matter. Mineral P were representing P rocks and P fertilizers, and recycled P were represented by MAP and HAP without specification. The study objects were the scenario of import based mineral P and the scenario of domestic based recycled P.

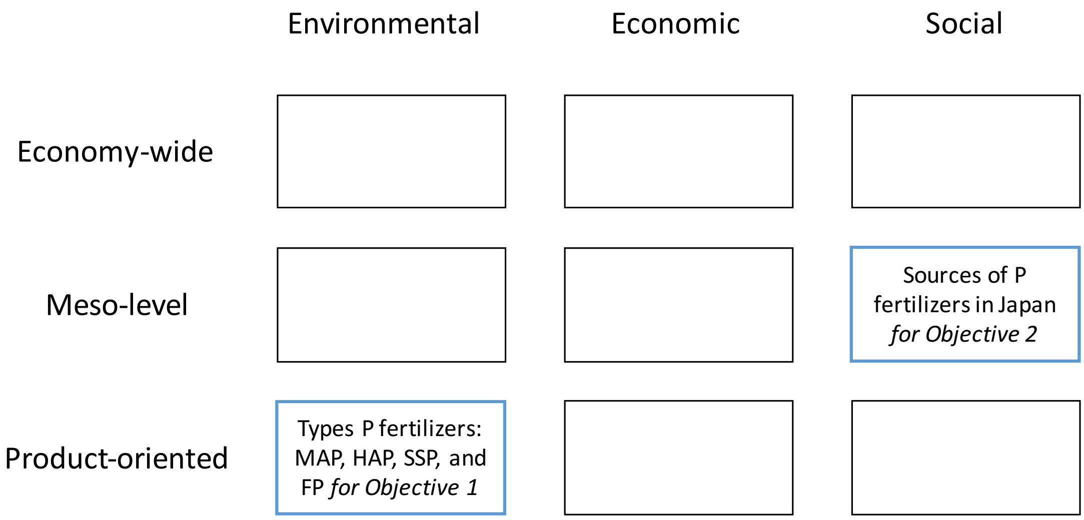

Figure 3-1. Overview of the study objects for Objective 1 and Objective 2 in the LCSA framework proposed by Guinee et al. [40].

3.2. Selected types of P fertilizers

The four selected types of common P fertilizers in Japan were MAP, HAP, SSP, and FP. However, at the moment, the production of recycled P was much lower than the mineral P. The annual production of recycled P was around 420 metric ton for MAP, 650 metric ton for HAP [13]; and mineral P were 124,298 metric ton for SSP, and 6,782 for FP [73].

In Objective 1, a comparison of environmental impacts among the four fertilizers was performed based on the P content in each fertilizer. The P content was estimated based on the chemical formula and purity of the fertilizers. Table 3-1 showed the basic characteristics of the fertilizers.

Table 3-1. Characteristics of the four selected P fertilizers for the study in Objective 1.

	Recycled P		Mineral P	
	MAP	HAP	SSP	FP
Chemical Formula	$NH_4MgPO_4 \cdot 6H_2O$	$Ca_5(PO_4)_3(OH)$	$Ca(H_2PO_4)_2$	$CaO \cdot mMgO \cdot P_2O_5 \cdot nSiO_2$
Additional nutrients	N, Mg	-	-	Mg
Releasing Characteristic (Solubility)	Slow	Slow	Fast	Slow

In agronomy, the four P fertilizers exhibited different characteristics when being applied to a farmland. In addition to P nutrient, MAP and FP contain extra ammonium (or nitrogen) and magnesium nutrients, which benefit the soil. The solubility, or the rate of releasing P nutrient, was fastest in SSP [16]. The solubility does not represent efficiency, and instead affects the farming practices, such as the required frequency of fertilizer application.

Figure 3-2 shows the overview of MAP and HAP processes in wastewater treatment plants. The production of the MAP and HAP are briefly described below.

MAP, commonly known as struvite, is produced in three WWTP in Japan—Fukuoka, Kobe, and Matsue City [13]. In the case of Matsue City, the technology is known as PHOSNIX, developed by

Unitika Ltd [74]. It is an add-on process to existing facilities. Before the introduction of PHOSNIX, to remove nitrogen and P, the biological treatment of anaerobic/anoxic/oxic tanks, or A2O process, was used. Polyaluminum chloride (PACl) was needed as a coagulant. The sediment from biological treatment was then treated in an anaerobic digestion process. The digested sludge was dewatered using ferric coagulants, such as ferric chloride or ferric sulfate, was used to cope with a wider range of pH. The final sludge was then sent to disposal, while the filtrate had to be retreated in primary clarifier. The introduction of PHOSNIX redirects the filtrate to struvite production plants before returning to primary clarifier. Struvite seed is provided to grow struvite crystal in the tank. Magnesium hydroxide is added as ingredient and sodium hydroxide is added as pH adjuster. As a result, struvite is produced and treated water is feeding back to treatment system.

HAP, is a form of recovered P from incinerated sludge ash, a waste from WWTP. HAP is produced at two incineration facilities of WWTP in Gifu and Tottori City [13]. In the case of Gifu, P was extracted as phosphate anions by alkaline solution at the temperature of 50 to 90 degree Celsius. Low P ash is then separated into a solid-liquid separator. The solid by-product, dephosphorized ash, is washed by pH 5 water (maintain by sulfuric acid) to meet the standard for soil disposal. The concentrated P solution is precipitated with the addition of slaked lime. P is collected as calcium phosphate with a solid-liquid separator.

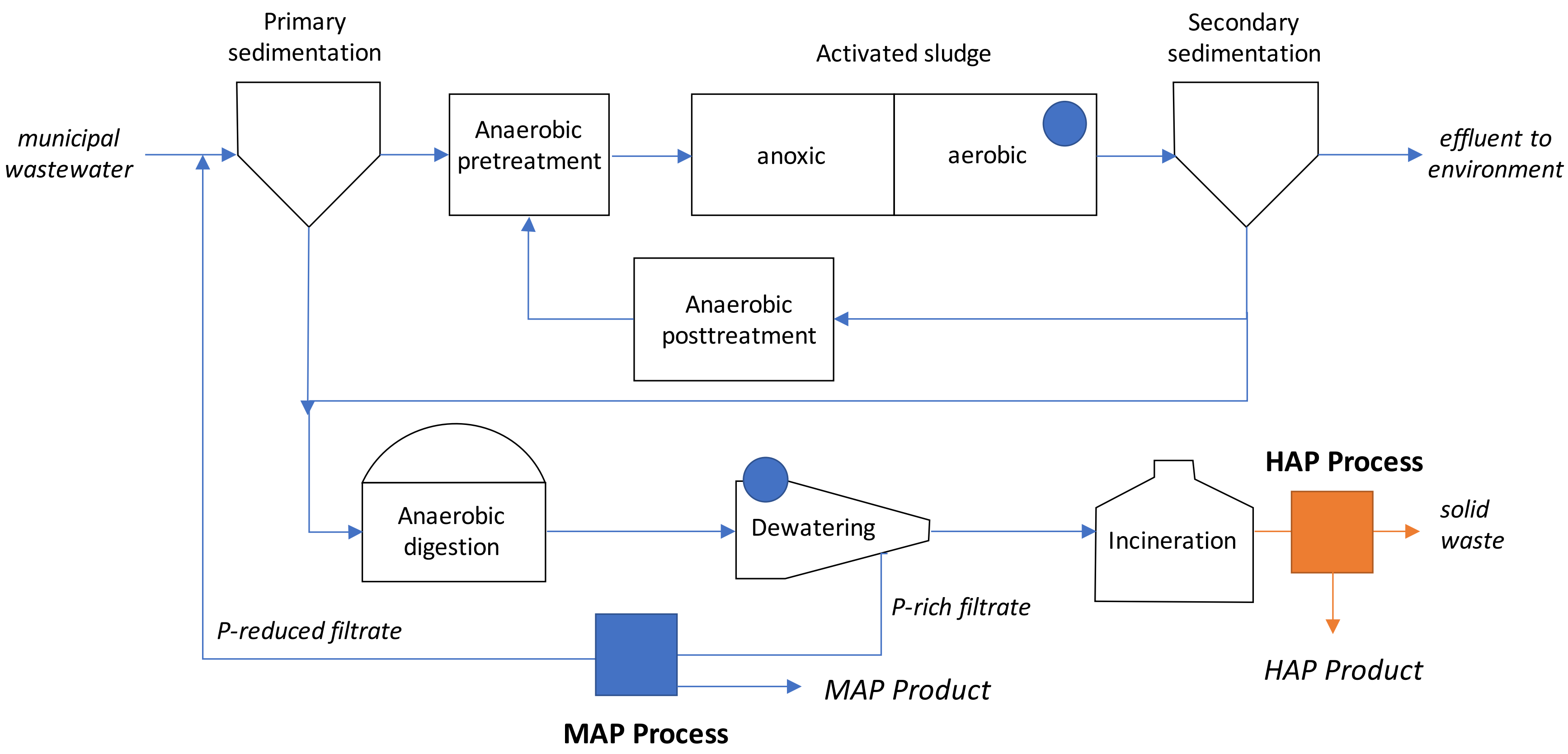

Figure 3-2. The overview of MAP and HAP processes in wastewater treatment plant based on Reference [14]. (Blue circles show the consequential effect of reducing coagulants requirement due to the introduction of MAP process.)

3.3. Sources of P fertilizers in Japan

P rock is a natural resource that is highly concentrated in a handful of countries [75]. Morocco and Western Sahara, China, United States, and Jordan control 85, 6, 3, and 2 percent of the world P reserves， respectively [76]. Japan has no mineral P deposit, and therefore has to rely on imported P sources.

Figure 3-3 presents the simplified P production and consumption system of Japan. The production system shows the raw P material acquisition activities, i.e. P rock mining and P recycling, and the P fertilizer production activities. Japan either directly imports P fertilizers from China and US, or self-produces P fertilizers based on P rocks import from China, South Africa, Jordan, and Morocco. Small amounts of recycled P are supplied to the fertilizer production， as a domestic source of P.

In Objective 2, a comparison of social impacts associated with mineral and recycled P was conducted based on the sources of P fertilizers. However, depending on the market mechanism and other acquisition issues, the sources of P import were not constant.

Figure 3-4 shows the statistic of country-based import of P rocks in the past 15 years. Although the total amount of P rocks import is decreasing rapidly, China, South Africa, Jordan, and Morocco remain as the major import sources to Japan.

Figure 3-5 shows statistics of country-based imports of ammonium P fertilizers, a main form of imported P fertilizer, during the past 15 years. Unlike imports of P rocks, the sources of P fertilizers show more changes. An increasing trend of imports from China and a decreasing trend of imports from the United States were observed.

A sharp drop of imports in around 2008 and 2009 was observed in both P rocks and P fertilizers import. This was due to the P price spike event in the international market. Figure 3-6 shows the average P rock import price in Japan. Fluctuation in price are becoming more obvious in the last decade.

For domestic production of recycled P, only about 1,000 metric ton are currently being produced [13]. However, the potential of recycling from WWTP was relatively large. Figure 3-7 shows a material flow analysis of P based on Reference [77]. The total available P collected in the sewer system was 52,750 metric ton. Therefore, a scenario of maximum recycling—without considering loses—would be able to replace 15% of P rocks import in Japan. Although other recycled P options, such as waste P in iron and steel industry and manure from livestock, are available, this study would focus only on the P from sewage system or WWTP, as the applications and technologies for different recycled P source would be very different.

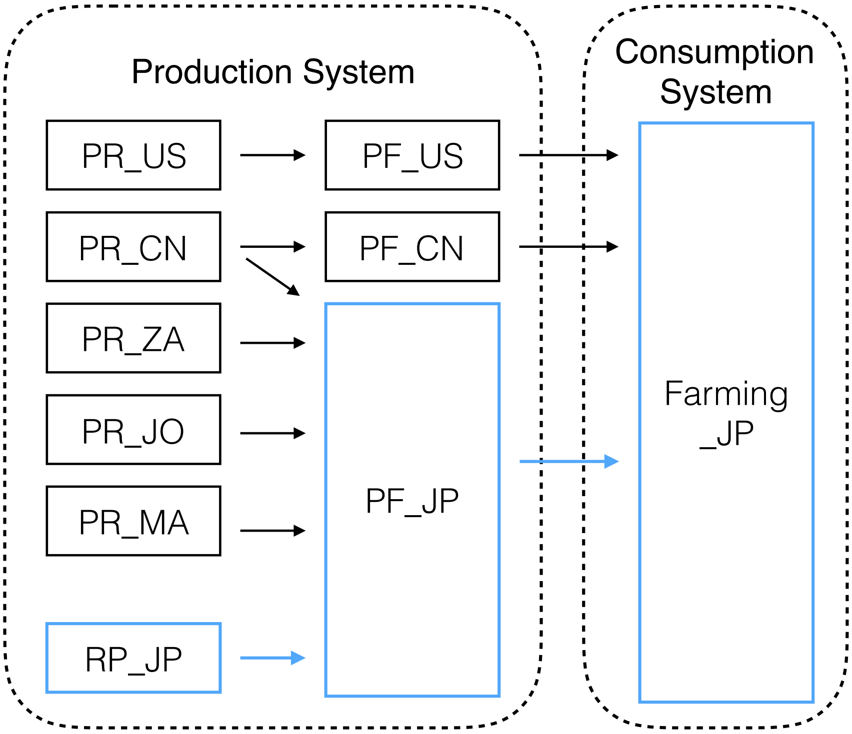

Figure 3-3. A simplified P fertilizers production and consumption system that shows the activities taking places in different countries.

(Blue lines: domestic activities, black lines: imported activities; PR: P rock mining, RP: recycled P production, PF: P fertilizers production, US: United State, CN: China, ZA: South Africa, JO: Jordan, MA: Morocco, JP: Japan).

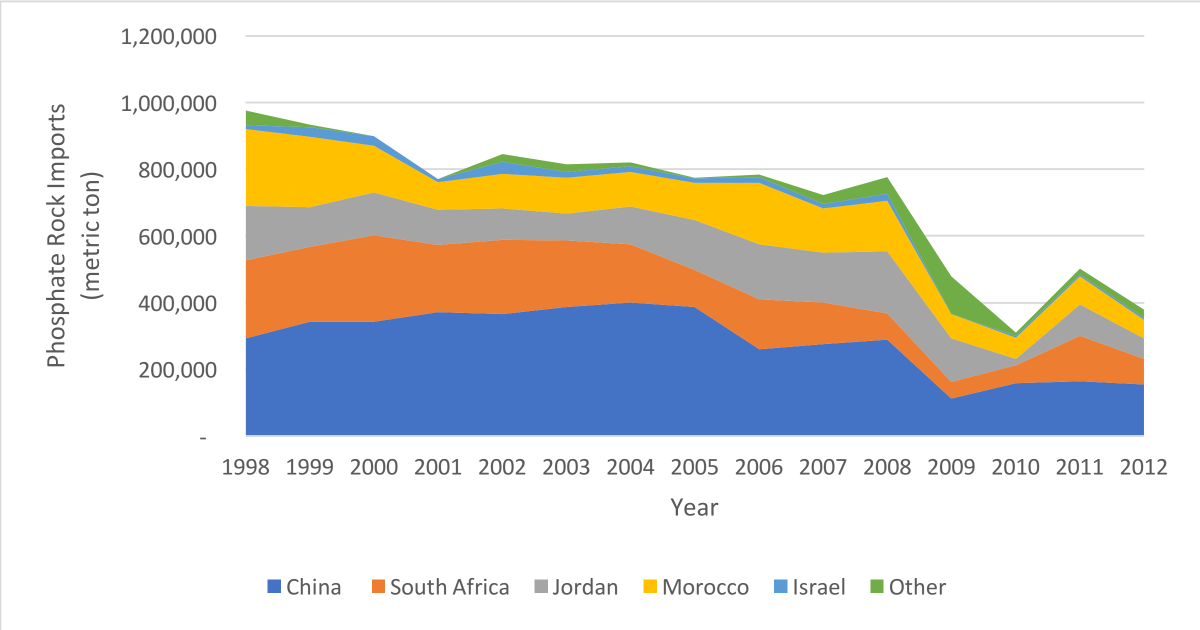

Figure 3-4. **Country-based import sources of P rock in Japan for the past 15 years. (Based on statistic from 財務省『貿易統計』[73])**

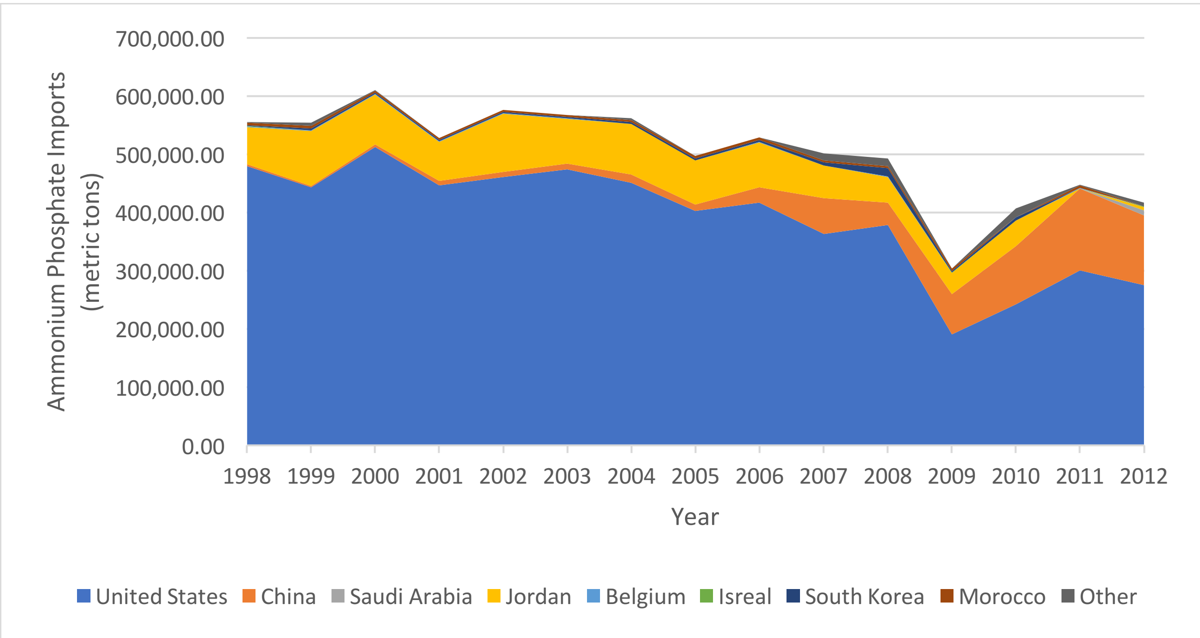

Figure 3-5. Country-based import sources of Ammonium P fertilizers in Japan for the past 15 years. (Based on statistic from 財務省『貿易統計』[73])

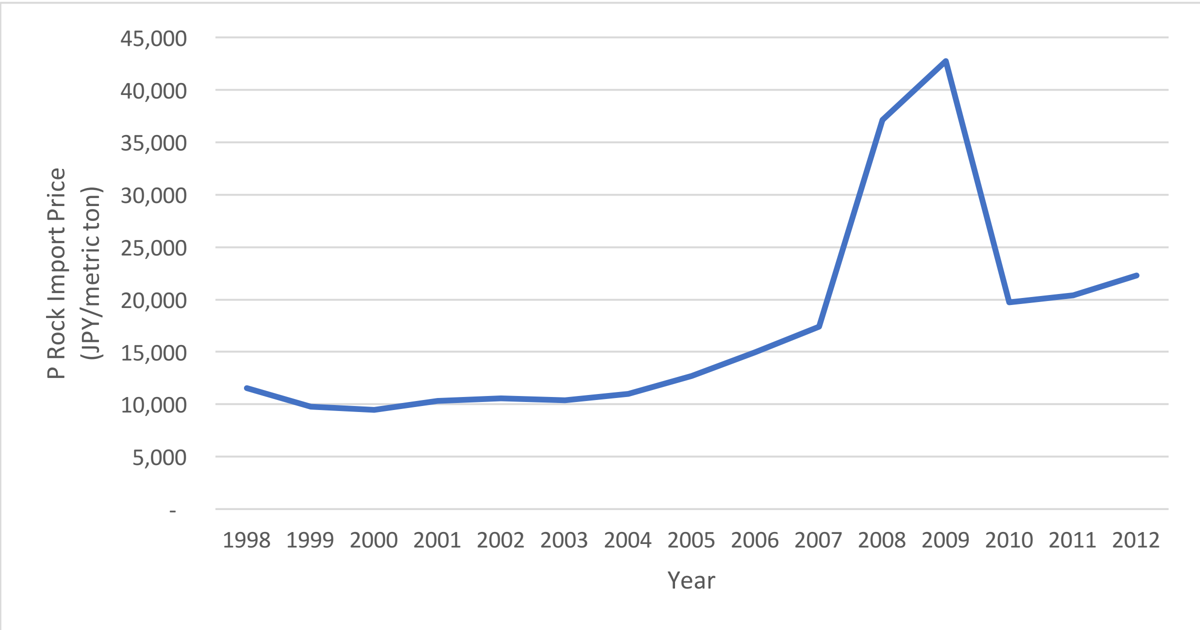

Figure 3-6. Average P rock import price in Japan for the past 15 years.

(Based on statistic from 財務省『貿易統計』[73])

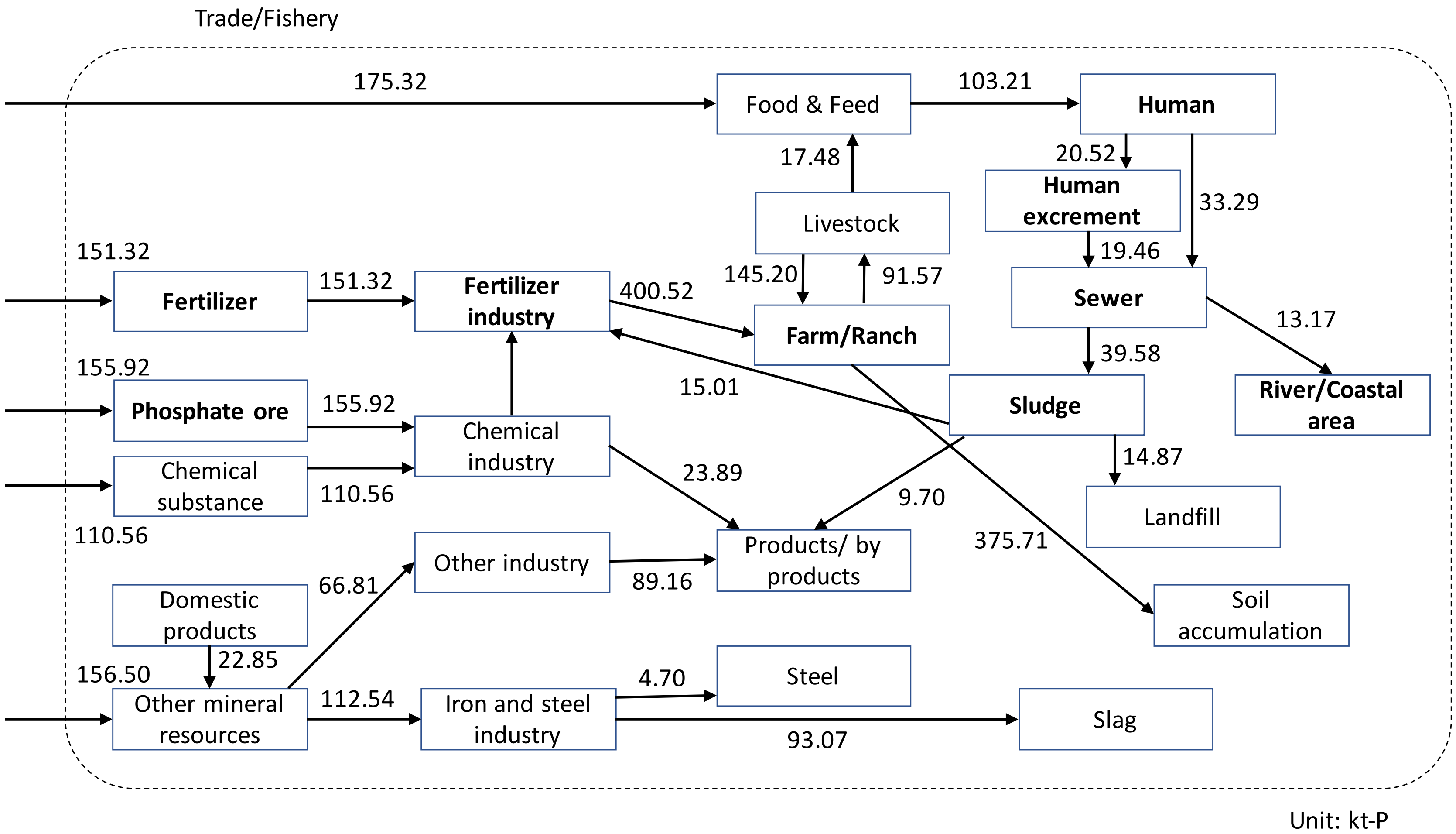

Figure 3-7. Overall material flows of P in Japan, recreated based on Reference [78].

4. METHODS

This chapter describes the methods of LCA for quantifying the environmental impact of mineral and recycled P fertilizers production (Section 4.1) and SLCA for semi-quantifying the social impact associated with consumption of mineral and recycled P fertilizers in Japan (Section 4.2).

4.1. LCA for environmental impact assessment

4.1.1. Goal and Scope Definition

The goal was to develop a comparative LCA framework to support the decision making of P recycling policy. A consequential LCA model was developed to compare the environmental performances of producing recycled P and mineral P. The environmental impacts were subsequently interpreted in monetary terms to better communicate with policymakers.

A case study of two recycled P fertilizers, MAP and HAP, was conducted. Two mineral P, SSP and FP, were used as references for comparison. The chosen functional unit was 1 kg of P content in respective P fertilizers products. The study did not account of differences in P releasing characteristics, as no reliable model was available. Also, the study did not include the agronomic value of magnesium, as no reference product was available.

Two environmental impacts categories were evaluated: GWP and eutrophication potential. The greenhouse gases were characterized as kg CO_2-equiv. based on 100-years GWP impact in IPCC 2007 method [79]. The nutrients in the effluent was characterized as PO_4-equiv., based on Heijungs' 1992 eutrophication potential estimation method [80].

Figure 4-1 shows the overall system boundary in this study. MAP and HAP were produced from wastewater and incinerated ash, respectively, while SSP and FP were both produced from P rocks.

A cradle-to-gate scope was applied to the products, which excluded the life cycle stages of farming, human consumption, and WWTP operation. The life cycles of recycled P, MAP and HAP, were treated as independent processes to SSP and FP. In other words, no recycling loop was considered. In reality, a) most P fertilizers applied on farms remained in soil, and only a small fraction go into the food chain, and b) most P in wastewater is originally from imported food sources as the food self-sufficiency rate in Japan is low [77].

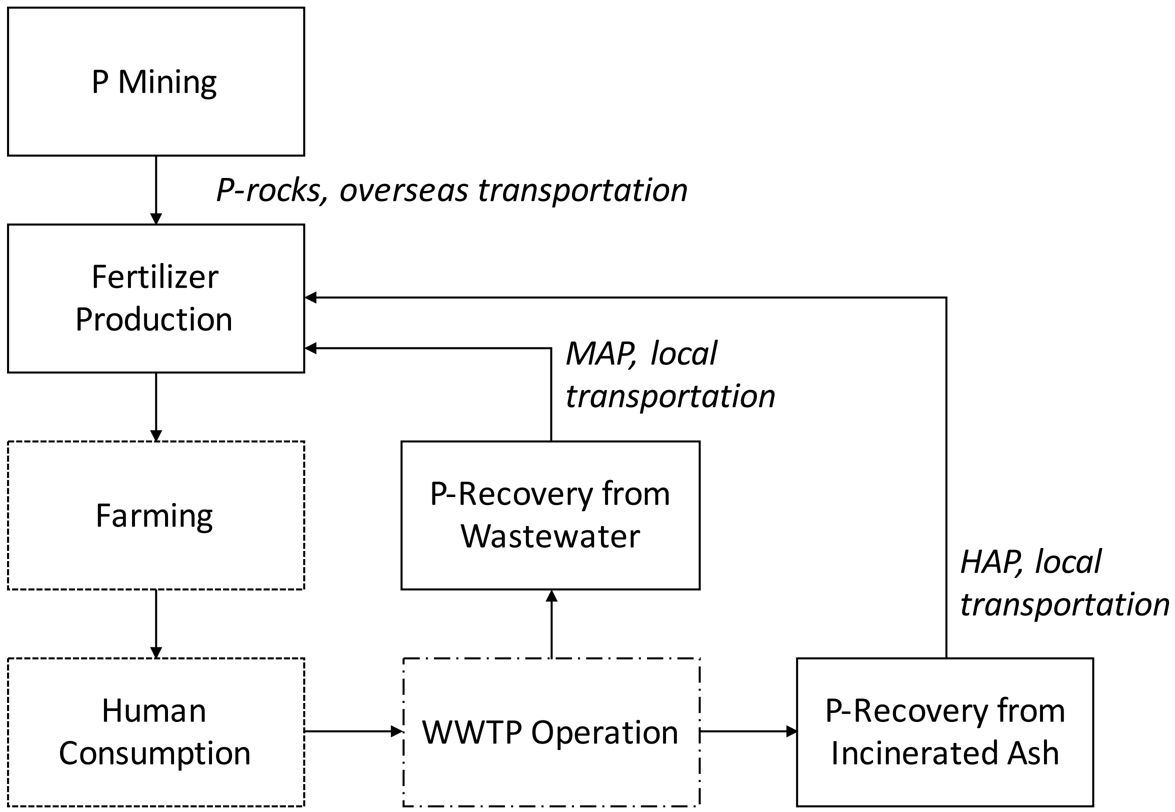

Figure 4-1. Overall system boundary of the LCA study. Life cycle stages of farming, and human consumption are excluded; WWTP operation is partially included in the consequential-LCA.

4.1.2. Inventory of Recycled P Fertilizers Production

For MAP, the author modelled the process flow based on the case study of Lake Shinji East WWTP in Matsue City, Japan. Data was collected from personal contacts in Hitachi Zosen Company (the developer; formerly, it was Unitika Ltd., which was acquired by Hitachi Zosen Company later), and other literature [74].

For HAP, the author modelled the process flow based on the case study of North WWTP in Gifu City. Data were estimated from a preliminary study report, LOTUS Project, which was submitted to Japanese Ministry of Land, Infrastructure and Transport in 2007 [81].

Infrastructure inventory

To precipitate MAP from wastewater, an individual reactor tank equipped with blower and hopper was required after the sludge digestion and dewatering processes. This facility was an add-on to the original WWTP, and therefore required new holding facilities. The author estimated the use of two main construction materials, i.e. 32.7 t of steel and 146.5 t of reinforced concrete, for a reactor with 500 kg/day MAP production capacity based on the floor plan of Lake Shinji East Plant [15]. Other existing WWTP facilities were excluded in the assessment. Because their primary function was to treat the wastewater instead of recovering P. The author assumed the infrastructure had a lifespan of 20 years based on the consultation with personnel from Hitachi Zosen. To precipitate HAP, several reaction tanks were required to extract P from sludge ash in a multistep process. Similarly, this facility was an add-on to the existing incinerator plant. Due to the unavailability of on-site data, the author assumed the total construction material consumption was the same as the MAP facilities.

Operation inventory

Table 4-1 and Figure 4-2 show the inventory and process flow of the operation phase respectively. For MAP precipitation, chemical $Mg(OH)_2$ is added based on 1 : 1 molar ratio of Mg^{2+} : PO_4-P; 43.6 kg $Mg(OH)_2$ is therefore needed for 500 kg MAP production each day. Other chemical combinations such as $Mg(Cl)_2$ and NaOH (as pH adjuster) were possible to perform the reaction, but the overall chemicals requirement would be costlier and less effective. Electricity is used to pump the filtrate into MAP reaction tank. For HAP production, P is extracted from the sludge ash by adding NaOH alkaline solution at a high reaction temperature, 50 °C to 90 °C. Solid-liquid separation is then performed to separate high P concentration liquid extract. HAP is finally precipitated with chemical $Ca(OH)_2$. Due to the unavailable of data, both of the products were assumed to have 200 km transportation distance to domestic fertilizer producing factory.

Table 4-1. Life cycle inventory for MAP and HAP production.

Items	Amount	Unit	Reference
MAP process			
MAP production	500	kg MAP/day	[74]
$Mg(OH)_2$ use	43.6	kg/500 kg MAP	Calculation
Electricity use	660	kWh/500 kg MAP	[15]
Additional P effluent reduction	0.39	kg total P/500 kg MAP	[74]
Avoided $FeCl_3$	392	kg/500 kg MAP	[3]
Avoided N fertilizer	28.5	kg/ 500 kg MAP	[74]
HAP process			
HAP production	300	t HAP/year	[13]
NaOH use	0.121	kg/kg HAP	[81]
$Ca(OH)_2$ use	0.431	kg/kg HAP	[81]
H_2SO_4 use	0.039	kg/kg HAP	[81]
Electricity use	3.373	kWh/kg HAP	[81]
Transport			
Local truck transport distance	200	km	Estimation

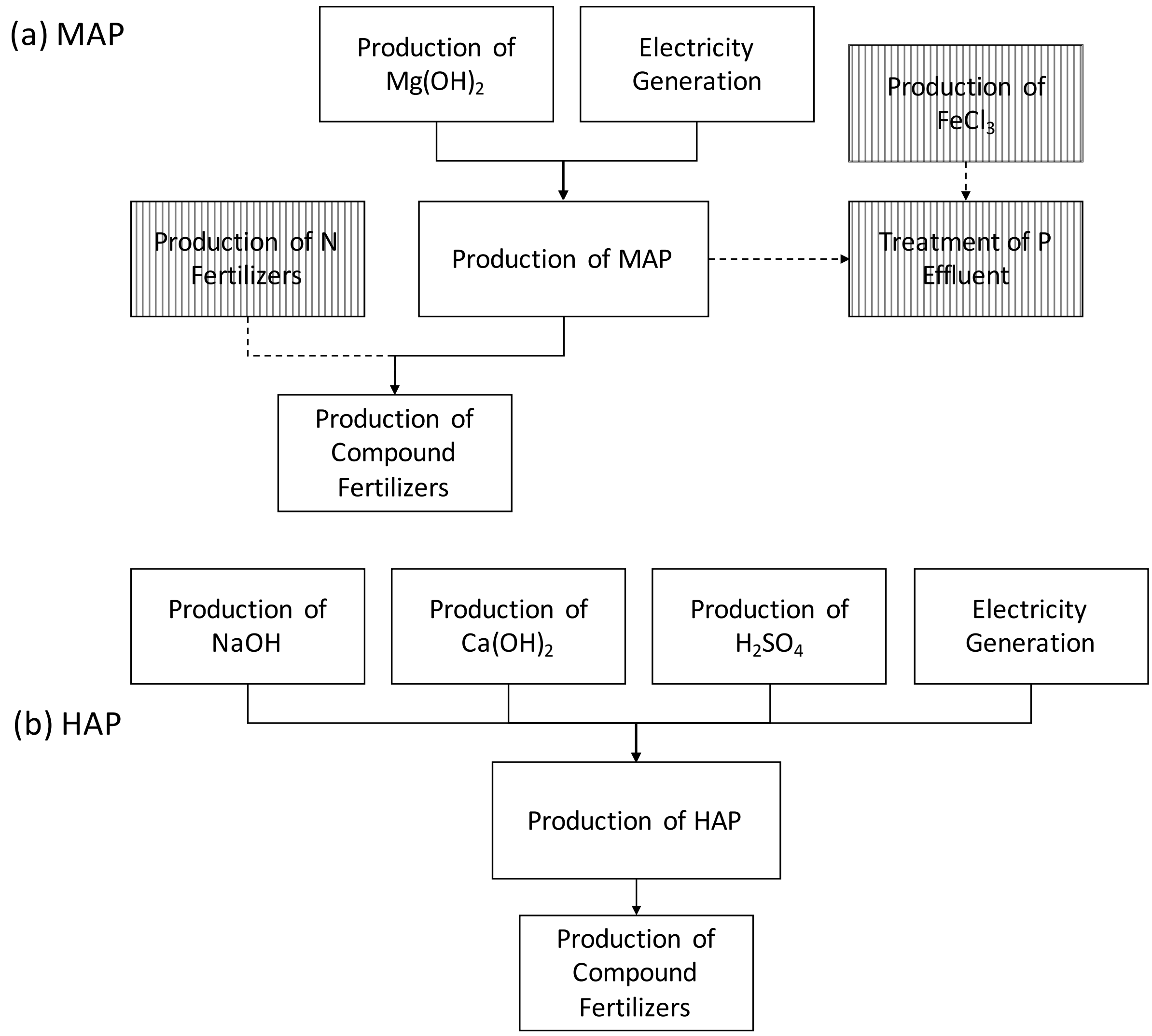

Figure 4-2. Process flow of (a) MAP production and (b) HAP production. Processes for consequential LCA considerations are highlighted in the patterned boxes in (a) MAP production.

Consequential Life Cycle Modelling

Consequential LCA estimates how pollution and resource flow within a system change in response to a change in an output of the functional unit [42]. As the introduction of MAP production has multiple consequences affecting the WWTP operation and fertilizer production, a consequential LCA model is more appropriate to evaluate performance.

Figure 4-2 (a) showed the two main consequential considerations for MAP production. First, the production of MAP could substitute a P removal process in WWTP, which often requires substantial use of coagulants such as $FeCl_3$ in the A2O process (a biological treatment process) and sludge dewatering process. In the case study, the MAP production not only substituted the P removal process, but it also achieved a lower P effluent concentration—0.4 mg/L total P effluent in comparison to 1 mg/L total P. Therefore, the author estimated the avoided usage of coagulants of $FeCl_3$ and credited the effect to MAP production.

Second, from an agronomic perspective, MAP consists of 9.8% magnesium and 5.7% nitrogen in addition to P nutrient content. Since MAP was used to produce NPK compound fertilizer, the author assumed an equivalent amount of nitrogen fertilizer requirement was avoided by MAP production. However, the value of magnesium was not considered although it was especially useful for grassland maintenance in farming. Unlike nitrogen, magnesium was not available as sole fertilizer. An alternative was to compare MAP with FP, as both of them contained magnesium.

The overall workflow of environmental impact analysis for MAP in wastewater treatment plant with consequential-LCA framework is summarized in Figure 4-3.

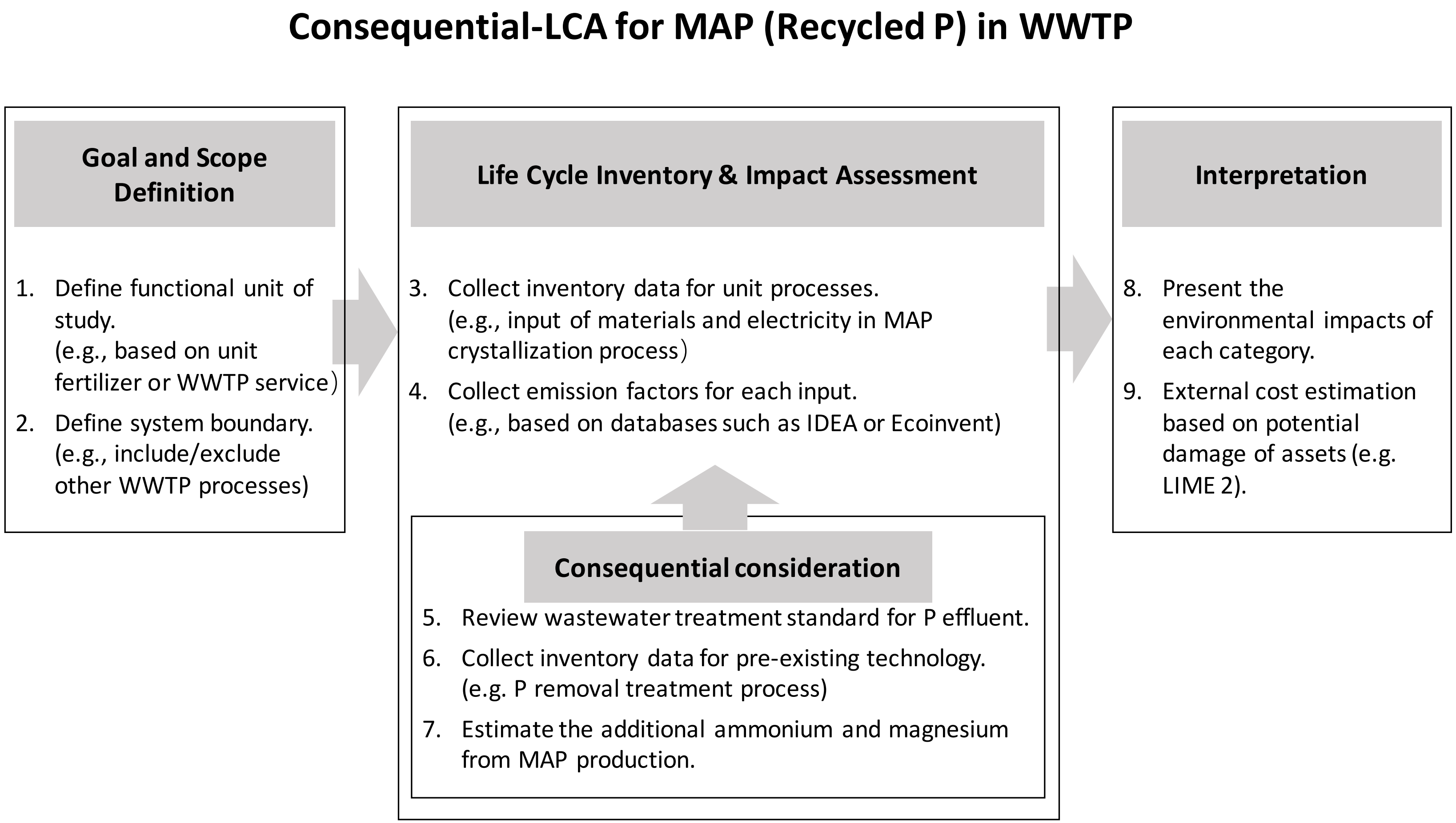

Figure 4-3. Workflow of environmental impact analysis for MAP (recycled P) in wastewater treatment plant with consequential-LCA framework.

4.1.3. Inventory of mineral P fertilizers production

Japan imports mineral P in the forms of preprocessed P-rocks from China, South Africa, Jordan, Morocco, and other countries. The sources of P-rocks change annually based on the market price and purchasing agreements. Imported P-rocks are processed into straight P fertilizer, SSP, or mixed P fertilizer, FP. SSP is commonly packed with nitrogen and potassium to form NPK compound fertilizers. FP is produced through high temperature mixing of Serpentinite rocks and P-rocks. The inventory for SSP and FP production were adapted from IDEA, a Japanese LCA database. Due to the multiple import sources of P rocks and multiple destination points, the author assumed the transportation distances for P rocks were 8,500 km by ship and 125 km by truck.

4.1.4. External Cost Estimation with LIME 2

To estimate the external cost, the environmental impacts of GWP and eutrophication potential were characterized as a damage function of social assets in monetary terms. The characterization was based on LIME 2, an endpoint modelling method developed for Japan [82]. Other safeguard subjects in LIME 2, such as human health measured in DALY, or Disability-Adjusted Life Year, are not covered in this estimation.

GWP was characterized based on three subcategories: a) loss of land caused by sea level rise; b) decrease the productivity of rice, corn, and wheat caused by climate change; and c) energy consumption due to behavior change in heating and cooling system. As a result, the damage factor was 0.3 JPY/kg CO2-equiv.

The eutrophication potential was characterized based on the damage on fishery production in the past pollution events in inner bays of Tokyo, Ise, Mikawa, and Osaka. The damage factor was 318 JPY/kg PO_4.

With LIME 2 damage function of social assets, the author estimated the external environmental cost for the P fertilizers productions. Then, compared the potential benefits of replacing mineral P with recycled P.

4.2. SLCA for Social Impact Assessment

The SLCA in this study followed the basic technical framework recommended by the UNEP-SETAC [46], which included defining the goal and scope of the study (Section 4.2.1), conducting an inventory of data (Section 4.2.2) and performing a social impact assessment (Section 4.2.3). To reflect the objectives of the study, improvements and changes were made. In Section 4.2.2, the author supplemented the inventory with additional P-related social indicators and proposed an alternative estimation of activity coefficient (or intensity of activity). In Section 4.2.3, the author designed a systematic social impact assessment framework to effectively evaluate and compare the options of P fertilizers consumption in Japan.

4.2.1. Goal and Scope Definition

The goal of this study was to support the P recycling policy by contrasting the social impacts associated with the consumption of mineral based P fertilizers and recycled-based P fertilizers in Japan. Based on the Guidelines, the author developed a systematic social impact assessment framework for mineral P fertilizer and recycled P fertilizer from WWTP to support the future debate on the inclusion of social externalities. The functional unit defined was 1 kg of mineral or recycled P fertilizer supplied to a farmer in Japan. Due to the semi-quantitative treatment of the social impact inventory indicators, the functional unit was only scalable based on the activity coefficient (introduced in Section 4.2.2), and comparisons of two sets of scenarios were discussed in Section 4.2.3. From a life cycle perspective, the scope of the study consisted of a production system where P rocks were mined and P fertilizers were produced; and a consumption system where P fertilizers were applied to farmland (Figure 3-3). In the production system, three main pathways of P fertilizers production were identified: direct import of P fertilizers from the United States and China, import of P rocks from China, South Africa, Jordan and Morocco with local fertilizer production, and recycling of P nutrient with local fertilizer production. In the consumption system, only farming activity in Japan was considered.

The aim of the SLCA was to evaluate the impact of activities on the relevant stakeholders. The author selected the workers and local communities in respective countries for the production activities, and individual farmers and society for the consumption activities in the assessment. Each stakeholder category was paired with a set of social impact categories that potentially affected their well-being such as labor rights and decent work in the case of workers. The categorization of the stakeholders and social impacts were based on the Guidelines [46]. Table 4-2 summarizes the stakeholders and social impact categories in this study. The details of how each stakeholder in the P supply chain may be impacted were reviewed in References [10, 11].

Table 4-2. The summary of stakeholders and social impact categories in the SLCA.

Activities	Stakeholders (in respective countries)	Social Impact Categories
Production system: Mining, fertilizer production, WWTP operation	Workers	Labor rights and decent works, health and safety, human rights
	Local communities	Health and safety, human rights, governance
Consumption system: Farming	Farmers	Livelihood
	Society	P security, commitment to sustainability issues

The system boundary of this study included only three simplified life cycle stages: raw P acquisition (i.e., P rock mining and recycled P production); the production of P fertilizers; and farming, with specific activity sites. Background processes such as transport and electricity production were excluded to focus the discussion on P-specific social impacts. As shown in Reference [37], even though the inventory for the background processes was possible, the linkages to foreground processes or the methodology for weighting were weak, especially when dealing with multiple stakeholder and impact categories.

4.2.2. Inventory of social indicators and activity coefficient

Two sets of inventories were conducted: the social impacts indicators that characterized the impacts on stakeholders, and the activity coefficient that weighted the attribution of each production activity for producing one functional unit.

Social impact indicators

An indicator approach was applied to evaluate the social impacts [83]. 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 general descriptive indicators and nine specific descriptive indicators. The categorization of indicators was based on Kruse et al. study [35].

General descriptive indicators, which characterize the social impacts related to generally recognized societal value, were directly collected from the SHDB. Most of these data were originally collected from the databases of reputable organizations, e.g., the percentage of total child labor in a country was taken from the International Labor Organization. These quantitative and qualitative data were classified into four risk levels: low, medium, high, or very high by the SHDB. The rules for classification were primarily based on a quartiles approach or the expert judgement from the New Earth's advisory board. For example, one country's data like "percentage of child labor in China" was compared with the global distribution of the data. The country's data were categorized as low risk if the data fell within the first quartile, which was lower than 4% in this case [58, 84]. The resolution of the data was constrained by data availability [85], so the highest resolution was at a country-specific sectors scale.

Specific descriptive indicators, which characterize the social impacts related to P industry-specific issues as described in the introduction, were collected from various literature and supporting documents in P studies. Initially, the author selected a set of indicators based on the concept of P security [10]. The selection was then improved based on the input from P experts (including Dana Cordell and Eiji Yamasue) at two recent academic conferences, the 5th P Summit in Kunming and the 12th Ecobalance Conference in Kyoto, and a P mining site visit in Kunming. The author summarized the selected specific descriptive indicators and the reasons for inclusion in Table 4-3.

The full list of indicators, characterized issues, resolution of data, rules of characterization, and sources were summarized in Table 4-4.

Table 4-3. Selected descriptive specific indicators and reasons for inclusion.

Categories	Social Themes	Selected Descriptive Specific Indicators	Reasons for Inclusion
Health and safety of local communities	Exposure to NORMs	Bq/kg U-238 series in P rock Bq/kg Th-232 series in P rock Bq/kg K-40 in P rock	U-238 series, Th-232 series, and K-40 are the types of naturally occurring radionuclide [86]. Natural P rocks in normal condition include them that vary among locations. They are concentrated in the waste of P industry, thus may pose health risk to the community.
Human rights of local communities	Indigenous rights	Identified indigenous issues related to P industry	P rocks is a tradable commodity that potentially causes conflicts in a community or a country. Current unresolved conflicts in the Western Sahara and Syria are most likely threatening the basic human rights of local communities [11].
Livelihood of individual farmers	Income	Ratio of income spending on P fertilizer	Farmers' affordability of fertilizers can be indicated by their income spending [10]. High spending on fertilizers will undermine the livelihood of farmers.
		Farm-gate cost of P fertilizers relative to market price	Farm-gate cost of P fertilizers are highly variable, depending on transportation and retail cost [11]. Lack of accessibility to P resources will increase the cost and thus undermining the livelihood of farmers.
P security of society	P import dependency	Ratio of import P and total P consumption	Natural P deposits are concentrated in a few countries. Countries depending on foreign P will be vulnerable to the price fluctuation in international market and changes in international politics [10].
Commitment to sustainability issue of society	Mineral P depletion	National mineral P consumption relative to global consumption (per ha farmland input)	P fertilizers application on farmland are highly variable [33], depending on the soil condition, farmer's economic status, and habits. Excessive use of P on farmland lead to a waste of resource.
	Education and responsibility	Effort in promoting circular society [1]	Resource recycling is the key concept of circular society in Japanese context. Recycling P from WWTP enhances the effort for sustainable lifestyle.

Categories
Social Themes
Selected Descriptive Specific Indicators
Reasons for Inclusion
Health and safety of local communities
Exposure to NORMs
Bq/kg U-238 series in P rock
U-238 series, Th-232 series, and K-40 are the types of naturally occurring radionuclide [86]. Natural P rocks in normal condition include them that vary among locations. They are concentrated in the waste of P industry, thus may pose health risk to the community.
Bq/kg Th-232 series in P rock
Bq/kg K-40 in P rock
Human rights of local communities
Indigenous rights
Identified indigenous issues related to P industry
P rocks is a tradable commodity that potentially causes conflicts in a community or a country. Current unresolved conflicts in the Western Sahara and Syria are most likely threatening the basic human rights of local communities [11].
Livelihood of individual farmers
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Education and responsibility
Effort in promoting circular society [1]
Resource recycling is the key concept of circular society in Japanese context. Recycling P from WWTP enhances the effort for sustainable lifestyle.

Table 4-4. Full list of indicators, characterized issues, resolution of data, rules of characterization, and sources for the SLCA. (The descriptive general data were adapted from SHDB and the descriptive specific data were designed in this study.)

Stakeholders	Impact Categories	Social Themes	Characterized Issue	Data Indicators	Types of Data (Quantitative, qualitative)	Resolution of Data	Rules for Characterization	Original Sources
Workers	Labor rights and decent work	Child labor	Risk of child labor in country	Percent total child labor in country	Quan	Country	<4% = low, 4-10% = med, 10-20% = high, >20% = very high	ILO, US Department of Labor, UNICEF
		Forced labor	Characterization of ILO's forced labor regional estimates	Prevalence of forced labor by region	Quan	Region to country	<3 = low, 3-3.5 = medium, 3.5-4 = high, >4 = very high	ILO
		Excessive working time	Risk of excessive working time by sector	Percent of population working > 60 hours	Quan, Qual	Sector	<10% = low, 10-25% = medium, 25-50% = high, >50% = very high	US Department of State
		Freedom of association, collective bargaining, and right to strike	Risk of a country lacks or does not enforce freedom of association	Freedom of association rights	Qual	Country	Low = rights recognized, medium = allowed with minor restrictions, high =recognized but very limited, very high = no laws or laws against	ITUC
			Risk of a country lacks or does not	Collective bargaining rights	Qual	Country	Same as freedom of association rights.	ITUC

		enforce collective bargaining rights					
		Risk of a country lacks or does not enforce right to strike	Right to strike	Qual	Country	Same as freedom of association rights.	ITUC
Health and safety	Occupational injuries and deaths	Risk of fatal injuries by sector	Fatal injury rate by sector, per 100,000 workers	Quan	Country to sector	Low = <5, medium = 5-15, high = 15-20, very high = >20	Hamalainen et al. 2009
		Risk of non-fatal injuries by sector	Non-fatal injury rate by sector, per 100,000 workers	Quan	Country to sector	Low = <5000, medium = 5000-15000, high = 15000-25000, very high = >25000	Hamalainen et al. 2009
	Occupational toxics and hazards	Risk of death by exposure to carcinogens	Overall occupational cancer risk, deaths	Quan	Region to country	Based on the average of lung cancer, Leukemia, and Mesothelioma	Driscoll et al. 2005
		Risk of loss of life years by exposure to carcinogens	Overall occupational cancer risk, loss of life years	Quan	Region to country	Same as risk of death by exposure to carcinogens	Driscoll et al. 2005
		Risk of workplace noise exposure	Overall occupational noise exposure	Quan	Region	Low = <14, medium = 14-22, high = 22 -22.5, very high = > 22.5	WHO
Human rights	Gender equality	Risk of gender inequality in country	Overall gender inequity in country	Quan	Country	Based on the average of SIGI, Global Gender Gap Index, and GII	UNDP, SIGI, CIRI, World Bank

Local community	Health and safety	Exposure to NORMs	Risk of exposure to U-238	U-238 series in P ore[1]	Quan	Country	Low = <500, medium = 500-1000, high = 1000-2000, very high = >2000	NIRS
			Risk of exposure to radioactive Th-232	Th-232 series in P ore[1]	Quan	Country	Low = <500, medium = 500-1000, high = 1000-2000, very high = >2000	NIRS
			Risk of exposure to radioactive K-40	K-40 series in P ore[1]	Quan	Country	Low = <2500, medium = 2500-5000, high = 5000-7500, very high = >7500	NIRS
	Human rights	Indigenous rights	Risk of indigenous people are negatively impact at sectoral level	Indigenous sector issues identified	Qual	Country	Subjective judgement based on reported evidences	UNDESA
			Risk of indigenous people are negatively impact at P activity	Indigenous P issues identified[1]	Qual	Country	Subjective judgement based on reported evidences	Cordell et al. 2015

		High conflict zones	Risk of high conflict	Overall risk of high conflict	Qual	Country	Based on the average of Heidelberg Conflict Barometer, State Fragility Index, UN Refugee Agency Global Trends Reports, and the Conflict without Borders assessment	Heidelberg Institute, UN Refugee Agency, Conflict without borders
	Governance	Corruption	Risk of corruption	Overall risk of corruption	Qual	Country	Based on the average of Worldwide Governance Indicators, World Economic Forum, and Transparency International	Transparency International, World Economic Forum
Farmer	Livelihood	Income	Risk of unaffordable of P fertilizers	Ratio of income spending on P fertilizer[1]	Quan	Country	Expert judgement	Japan Agricultural Statistics
			Risk of overpriced of P fertilizers	Farm gate price of P fertilizers relative to international market price[1]			Expert judgement	IFA
Society	P Security	P import dependency	Dependency of foreign P	Ratio of import P and total P consumption[1]	Quan	Country	Expert judgement	Japan Agricultural Statistics
	Commitment to	Mineral P depletion	Risk of over consumption of P fertilizer	Mineral P consumption relative to global	Quan	Country	Expert judgement	Japan Agricultural Statistics

Sustainability issues			consumption, in per ha input[1]				
	Education and responsibility	Risk of hindering the promotion of circular society	Effort in promoting recycling[1]	Qual	Country	Expert judgement	Interview

[1] Specific indicators are marked.

[2]Abbreviation. ILO: International Labour Organization, UNICEF: The United Nations Children's Fund, ITUC: International Trade Union Confederation, UNDP: United Nations Development Programme, WHO: World Health Organization, SIGI: Social Institutions and Gender Index, CIRI: The CIRI Human Rights Data Project, NIRS: National Institute of Radiological Sciences, Japan, UNDESA: The United Nations Department of Economic and Social Affairs, IFA: International Fertilizer Industry Association

Inventory Results

The SLCA inventory results were shown in Table 4-5, 4-6 and 4-7. The risk level of individual activity, i.e. P rocks mining, P fertilizers production, and P recycling in respective countries, were represented in colors coding. For the production system, in overall, the potential impacts on workers (Table 4-5) were higher than local communities (Table 4-6). For the consumption system, the potential impacts on farmers and societies (Table 4-7) were higher in consuming mineral P than recycled P fertilizers. The impacts on farmers' livelihood was indistinguishable because the cost for recycled P fertilizers was subsidized by governments to match the price of mineral P fertilizers at the moment.

Table 4-5. Social impacts inventory for workers in P rocks mining (PR), P fertilizers production (PF), and P recycling (RP) in respective countries. (The risk levels of low, medium, high, and very high risk are indicated in green, yellow, orange and red respectively.)

Social Theme	Characterized Issue	Social Impact Risk Level (0: Low Risk, 1: Medium Risk, 2: High Risk, 3: Very High Risk)								
		PR_CN	PR_ZA	PR_JO	PR_MA	PR_US	PF_US	PF_CN	PF_JP	RP_JP
Labor Rights and Decent Work										
Child Labor	Risk of child labor in country	3	3	3	1	0	0	3	0	0
Forced Labor	Risk of forced labor in country	1	2	1	2	0	0	1	0	0
Excessive Working Time	Risk of excessive working time by sector	2	0	2	1	1	1	3	2	2
Freedom of Association, Collective Bargaining, Right to Strike	Risk that a country lacks or does not enforce collective bargaining rights	3	1	1	1	3	3	3	1	1
	Risk that a country lacks or does not enforce freedom of association rights	2	1	1	1	2	2	2	2	2
	Risk that a country lacks or does not enforce the right to strike	3	1	2	2	2	2	3	3	3
Health and Safety										
Occupational Injuries & Deaths	Risk of fatal injuries by sector	1	1	0	1	3	1	1	1	1
	Risk of non-fatal injuries by sector	1	1	0	1	1	1	1	1	1
Occupational Toxics & Hazards	Overall risk of death by exposure to carcinogens in occupation	3	1	0	1	1	1	3	0	0
	Overall risk of loss of life years by exposure to carcinogens in occupation	3	1	0	1	1	1	3	0	0
	Overall risks of workplace noise exposure, both genders	2	1	1	2	0	0	2	1	1
Human Rights										
Gender Equity	Overall risk of gender inequality in country	2	1	2	2	0	0	2	1	1

Table 4-6. Social impacts inventory for local communities in P rocks mining (PR), P fertilizers production (PF), and P recycling (RP) in respective countries.

Social Theme	Characterized Issue	Social Impact Risk Level (0: Low Risk, 1: Medium Risk, 2: High Risk, 3: Very High Risk)								
		PR_CN	PR_ZA	PR_JO	PR_MA	PR_US	PF_US	PF_CN	PF_JP	RP_JP
Health and Safety										
Exposure to Radioactive Waste	Risk of exposure to radioactive waste, U-238	0	0	1	3	2	2	0	1	0
	Risk of exposure to radioactive waste, Th-232	0	1	0	0	0	0	0	0	0
	Risk of exposure to radioactive waste, K-40	0	0	0	0	0	0	0	0	0
Human Rights										
Indigenous Rights	Risk that indigenous people are negatively impacted at sector level	2	2	0	0	3	0	0	0	0
	Risk that indigenous people are negatively impacted by P industries	0	0	0	3	0	0	0	0	0
High Conflict Zones	Overall risk for high conflict in country	3	3	2	3	1	1	3	1	1
Governance										
Corruption	Overall risk of corruption in country	1	2	1	2	0	0	1	0	0

Table 4-7. Social impacts inventory for farmers and societies in consuming mineral and recycled P fertilizers in Japan.

Social Theme	Characterized Issue	Social Impact Risk Level (0: Low Risk, 1: Medium Risk, 2: High Risk, 3: Very High Risk)	
		Mineral P	Recycled P
Farmers' Livelihood			
Income	Risk of unaffordable of P fertilizers	0	0
	Risk of overpriced of P fertilizers	0	0
P Security			
P Import dependency	Dependency on foreign P	3	0
Commitment to sustainability issues			
Mineral P depletion	Risk of over consumption of P fertilizer	3	0
Education and responsibility	Hinder the promotion of circular society	2	0

Activity coefficient

As P fertilizers in Japan are supplied from various countries (Figure 3-3), the author designed a set of activity coefficients to weight the production processes. The activity coefficient was defined as a weighting variable that gives a relative importance to different unit processes and different countries involved in the system [51, 58].

Two steps of weighting processes were involved in this assessment. First, the unit processes, i.e., P mining and P fertilizer production, were given an equal weight. This was to avoid giving preferential and discriminating treatment to any stakeholder and any social impact category associated with the two processes. Second, the site-specific processes were weighted based on the share of the import of P rocks and P fertilizers from each country. For P rocks, we collected the import data of 2012. Indirect use of P rock was also considered; in the case of USA and China where P was imported as P fertilizers, the author assumed an equivalent amount of P rocks was required. Although we realized that the concentration of P was different in P rocks and P fertilizers, this assumption was made due to a lack of detailed data. For P fertilizers, the author collected the import data of ammonium P fertilizers, which included monoammonium and diammonium P fertilizers, in 2012. The author assumed P fertilizer production in Japan was equivalent to the import amount of P rocks for the same reason. The data for P rock imports and P fertilizer production were cut-off at 8.26% and 5.21%, respectively. Some imports from the rest of the world were not included as these amounts were relatively small and were not stable sources to Japan. The results of the inventory are shown in Table 4-8.

For recycled P fertilizers production, the activity coefficients of WWTP operation and P fertilizers production were assigned as 0.5 and 0.5, respectively to avoid preferential treatment. The same social indicators were considered for MAP and HAP types of recycled P fertilizers, although the inputs to WWTP for producing MAP and HAP were different as background processes were not considered in this study.

Table 4-8. The activity coefficient was estimated based on the share of import from each country except for P fertilizers, which are partially produced domestically.

Activity	P Rocks (metric tons in 2012)	Activity Coefficient	Activity	P Fertilizers (metric tons in 2012)	Activity Coefficient
PR_US	275,729	0.19	PF_US	275,729	0.19
PR_CN	153,790	0.18	PF_CN	120,006	0.08
PR_ZA	78,051	0.05	PF_JP	349,210	0.23
PR_JO	60,000	0.04			
PR_MA	57,369	0.04			

P rock mining and P fertilizer production were given an equivalent weight, a total of 0.5 in each column. (PR: P rock mining, PF: P fertilizers production, US: United States, CN: China, ZA: South Africa, JO: Jordan, MA: Morocco, JP: Japan).

4.2.3. Impact Assessment and Interpretation

Social Impacts Hotspots

Before any advanced treatment of the data, the author identified the social hotspots within the life cycle of P fertilizers consumed in Japan as aggregating the social impacts across different stakeholders or social categories might lead to information loss, thus affecting the interpretation. Hotspots of production activities were identified based on the count of high risk and very high risk social indicators involved in each activity [53], and showed the production activities that were having the most impacts on society, and thus should be avoided. In contrast, hotspots of social indicators were identified based on the count of high risk and very high risk activity shown in each indicator and showed the impact categories that were most concerned in the supply chain of P.

Comparisons of mineral and recycled based P fertilizers

A systematic social impact assessment framework was developed to communicate the overall social impacts effectively. First, the author harmonized the inventory data by assigning a score to represent the social risk level of each activity: 0 as low risk, 1 as medium risk, 2 as high risk, and 3 as very high risk. All quantitative or qualitative inventory data were therefore converted to a simple score. Then, the author multiplied the score of each activity to the corresponding activity coefficient. For example, the child labor in P rock mining in China (score 3) was multiplied by its corresponding activity coefficient (0.18) and yielded a score of 0.54. Aggregating the score of all site-specific production processes resulted in a score that showed the performance of a social indicator of P fertilizer consumption based on current consumption choice in Japan. Next, the author performed a series of aggregation by the weighted average risk level of the data indicators, social themes, social impact categories, and stakeholder's groups accordingly, to obtain the final social impact score for the fertilizer choice. For example, the final score of "worker's labor rights and decent work", was based on the average score of "child labor", "forced labor", "excessive working time", and "freedom of association, collective bargaining, and rights to strike"; and the score of "freedom of association, collective bargaining, and rights to strike" was based on the average score of the three indicators.

Two sets of comparisons were made in this assessment.

A. The author compared the social impacts on stakeholders while consuming mineral and recycled-based P fertilizers in general. The author assumed that the impacts for mineral P fertilizers were based on the average of import sources and production processes, and recycled P fertilizers were based on a single source and production process only, which was Japan. Therefore, the assessment showed the marginal social impact that could be mitigated by changing the choices of P fertilizers for individual farmers in Japan.

B. The author conducted another comparison to show the social impact mitigation potential if Japan maximized the local P recycling from WWTP and substituted the P rock imports accordingly. The capacity of recycled P fertilizer production was constrained by the total available P collected in the WWTP. The author based the assessment on a P material flow analysis study in 2009 [77]. The estimation for P in the wastewater sector was based on population, and since the population of Japan has been mostly stagnant for the past 20 years, the author estimated a total of 52,750 metric tons of recycled P was available without considering the losses in the production processes, which could substitute 15% of P rock imports. The author assumed that total P fertilizer consumption was the same, and the maximum recycled P substituted the P rock imports from the highest social impacts source, i.e., China in this case. Furthermore, the activity coefficient was adjusted accordingly. This second comparison showed the maximum achievable social impact mitigation from implementing a compulsory P recycling policy at the nation (or country) scale by the Japanese Government.

The overall workflow of social impact assessment for P recycling policy with social-LCA framework is shown in Figure 4-4.

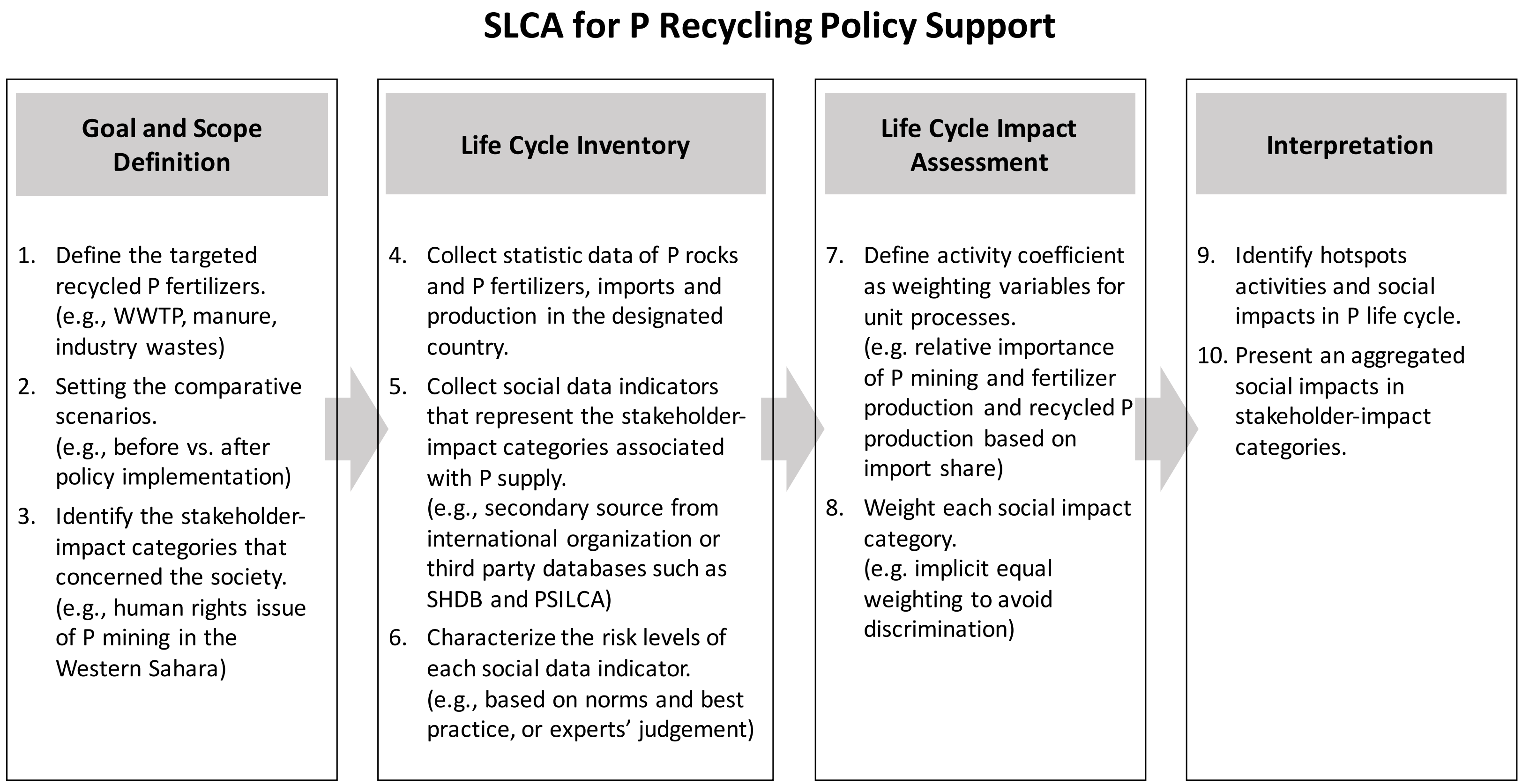

Figure 4-4. Workflow of social impact assessment for P recycling policy with social-LCA framework.

5. RESULTS AND DISCUSSION (ENVIRONMENTAL IMPACT)

5.1. Environmental Impact of Recycled and Mineral P Fertilizers Production

Figure 5-1 shows the results for GWP associated with MAP, HAP, SSP, and FP productions. The author highlighted the results of MAP, by showing both the results with and without considering CLCA (no consequential effect for HAP process was accounted). Without considering the CLCA effects, the mineral P fertilizers, SSP and FP, emitted much less greenhouse gases than the recycled P fertilizers, MAP and HAP. Among them, SSP emitted only 1.1 kg CO_2-equiv./kg P production, including the long-distance overseas transportation. However, with considering the consequential effects, GWP of MAP reduced significantly from 9.79 to 1.04 kg CO_2-equiv. /kg P production. Thus, the GWP performance of MAP was the lowest among all. This was caused by the avoided use of $FeCl_3$ coagulants and the credit to additional N fertilizer nutrient in MAP. The hotspots of GWP for recycled P production was electricity use, which contributed 75% to MAP for filtrate pumping, and 72% to HAP for reactors heating. This was followed by chemical use, 13% to MAP for $Mg(OH)_2$, and 24% to HAP for $Ca(OH)_2$ and NaOH. For mineral P production, the transport of P-rocks contributed to 31% to SSP and 10% to FP.

Figure 5-2 showed the results for eutrophication potential associated with MAP, HAP, SSP, and FP production. Without considering the consequential effects, mineral P fertilizers outperformed recycled P fertilizers with one to two orders of magnitude lower in PO_4-equiv. effluent. However, when considering the consequential effects, MAP would yield a negative impact on eutrophication. The LCA result showed 0.175 kg PO_4-equiv. effluent to water bodies was reduced by producing 1 kg P content. Because beside substituting P removal process, implementing MAP process further reduced total P concentration in the effluent of WWTP.

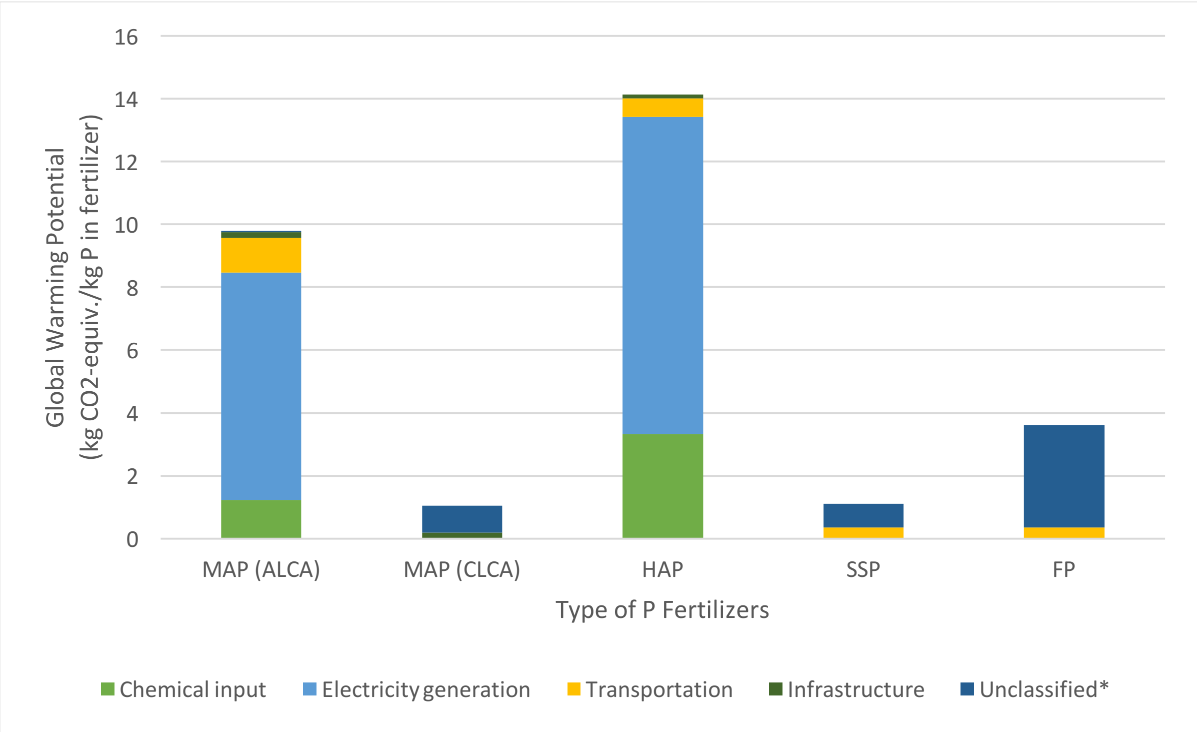

Figure 5-1. LCA results show the GWP for producing 1 kg P content in MAP, HAP, SSP, and FP fertilizers. The results of MAP are shown in both with (CLCA) and without (ALCA) the consequential LCA consideration. (MAP (CLCA) result includes avoided GWP, therefore result is shown without breakdown classification).

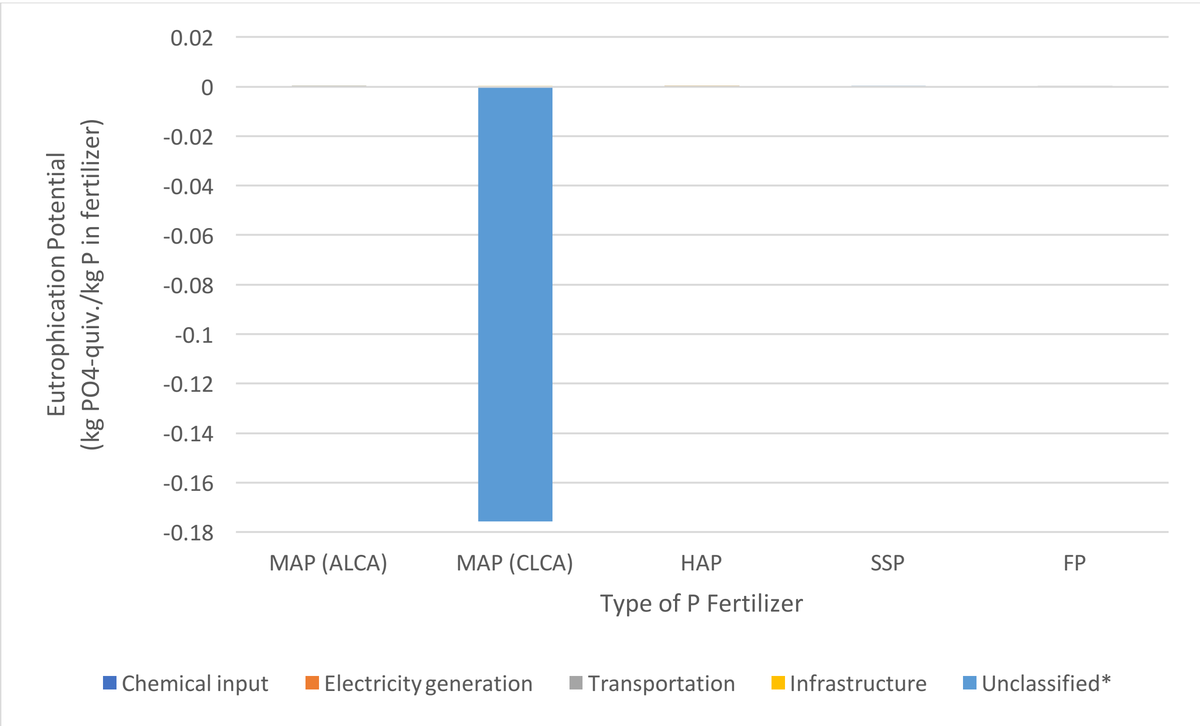

Figure 5-2. LCA results show the eutrophication potential for producing 1 kg P content in MAP, HAP, SSP, and FP fertilizers. The results of MAP are shown in both with (CLAC) and without (ALCA) the consequential LCA consideration.

5.2. Comparison of external cost with different strategy

The external costs for P fertilizers productions were characterized based on the potential social assets damage caused by global warming and eutrophication. To facilitate the discussion among policymakers, the author showed the benefits of different strategies in replacing mineral P with recycled P in Table 5-1. The net benefit was indicated in JPY, which estimated based on the differences in GWP and eutrophication when 1 kg of mineral based P was replaced with recycled P.

The most effective strategy was replacing FP with MAP (with CLCA consideration), where 56.6 JPY/kg P production could be saved. This was predominantly contributed by the reduction in eutrophication potential; the cost of GWP did not contribute much to the external cost. In addition, with current technology, introducing HAP to replace mineral P showed no environmental benefit.

Table 5-1. The net benefit of replacing 1 kg of mineral based P with recycled P based on the differences in external environmental costs (1 USD equal to 110 JPY, approximately).

Recycled P	Mineral P	$\Delta CO_2 = CO_{2,recycled} - CO_{2,mineral}$ (kg CO_2-equiv.)	$\Delta PO_4 = PO_{4,recycled} - PO_{4,mineral}$ (kg PO_4-equiv.)	GWP Mitigation Benefit (JPY/ kg P)	Eutrophication Mitigation Benefit (JPY/ kg P)	Net Benefit (JPY/ kg P)
MAP	SSP	-0.0621	-0.1756	0.02	55.84	55.9
	FP	-2.5812	-0.1756	0.77	55.85	56.6
HAP	SSP	13.0438	0.0001	-3.91	-0.04	-4.0
	FP	10.5247	0.0001	-3.16	-0.04	-3.2

5.3. Discussion

5.3.1. Significance of Consequential LCA

In Figure 5-1 and Figure 5-2, the author showed that the LCA results would be very different based on the consideration of consequential LCA consideration. Factors for consequential LCA of P fertilizers production were a) regulatory standards for wastewater discharged from WWTP, and b) accounting of additional nutrient in recycled P. In fact, the wastewater standards in the case study, Matsue City (1 mg/L total P), was higher than the Japanese national standards (2 mg/L total P). A P removal process was installed initially but was insufficient to solve the algal bloom in a local lake. Finally, MAP production process was introduced to substitute the P removal process, and the P effluent was reduced to 0.4 mg/L total P. The effects of consequential LCA was only notable because of this context. Since most of the wastewater standards in Japan are not high enough, MAP would not always environmentally friendlier than mineral P. Nevertheless, in this study, the author provided a reusable consequential LCA framework for the assessment of future scenarios.

An alternative way of accounting the consequential effects was discussed during the presentation in the 12th Ecobalance Conference [87]. The proposal was to considered P removal as part of the waste treatment scenario in the life cycle of mineral P. In this case, the addictive process of environmental impacts on mineral P would be easier to communicate, and still be fair in comparison to recycled P. However, quantifying mineral P fertilizers that ended up in WWTP was less realistic. In fact, most P fertilizers input to farmland will remain in the soil or flow into the water environment. Only small fraction of P goes into food for human consumption. And, most foods in Japan are imported. Therefore, it was rather unfeasible to account for the P removal process based on per unit of mineral P fertilizers consumption.

5.3.2 Recommendation for P recycling policy

In Table 5-1, the author showed that, in theory, replacing FP with MAP was the best strategy for environmental protection in theory. To examine the feasibility of the industrial transformation, the author looked into the FP characteristics and markets. First of all, the agronomic value of MAP is similar to FP. Therefore, it is practical for a farmer to make the changes. Globally, FP is a less popular form of P fertilizers. Japan is the main producer and consumer of FP [88], but the production of FP has been decreasing in recent years. In 2012, Japan produced 41,000 ton of FP. In contrast, the maximum potential of MAP production was 52,750 ton based on P available in sewage system [77]. Therefore, there is a potential to gradually transform from FP to MAP given sufficient support from the government.

According to Ministry of Land, Infrastructure, Transport and Tourism of Japan, there are around 2300 unit of WWTP systems in Japan [89]. Among them, only five are equipped with P recovery facilities at the moment. The priority for promoting P recycling policy would be selecting potential sites based on hotspots of eutrophication and scale of population. In a discussion with personnel from Hitachi Zosen, the author learned that MAP production in Matsue City was not operating at its maximum capacity, as the P influent was insufficient due to population decline, which could be an important issue in Japan.

5.3.3. Limitation and Uncertainties

The reliability of LCA depends on the quality of data. The assessment was mainly based on secondary inventory data and IDEA, a Japanese LCA database. A few factors were sensitive to our results: avoided $FeCl_3$ coagulant, avoided nitrogen fertilizer, and electricity use. An actual record of coagulant use before MAP introduction was not available, therefore, the author estimated $FeCl_3$ usage based on a reputable study [3]. Electricity use was estimated based on the pumping equipment in the system. Other factors, like material requirements for infrastructure, were high in uncertainty but less sensitive to the overall result.

This assessment was based on current state of mining and recycling technologies. In the future, mining of P rock is expected to be more difficult due to the depletion of high quality and easy-access P deposits. The energy and material input to the mining activity and the associated environmental impacts are likely to increase. In contrast, the efficiency of recycling P technology can be improved with a larger scale of implementation and development. Therefore, it could be expected that the benefit of recycling P will improve in the future.

In short, the author has developed and examined a comparative LCA framework for evaluating the environmental performance of recycled P and mineral P fertilizers production. A consequential LCA showed that MAP was the most environmentally friendly choice of fertilizers, based on the case studies. The author has estimated the external environmental cost of different promotion strategies to facilitate the policy debates. Finally, a policy recommendation for supporting the transformation of FP to MAP was made.

6. RESULTS AND DISCUSSION (SOCIAL IMPACT)

6.1. Hotspots of social impacts

Figure 6-1 showed the activity hotspots involved in supplying the P fertilizers in Japan, which were mining in China and Morocco, and fertilizer production in China. In 2012, direct P rock imported from China and Morocco accounted for 44% and 16%, respectively; the direct importation of P fertilizers from China accounted for 30%. This assessment raised concerns regarding the working conditions in China (i.e., labor rights and health and safety issues), and in protecting the human rights of indigenous communities in Morocco. It should be noted that the results were based on sectoral data, which could not distinguish between P mining and the mining of other minerals. A visit to the Yuntianhua Group in China, one of the world's leading P fertilizer production companies [90], showed that the working conditions in this country may be less severe than estimated. Therefore, the results must be used carefully. Nevertheless, it is acknowledged that the SHDB provided us with a reasonable estimation of social indicators, when collecting field data was not practical.

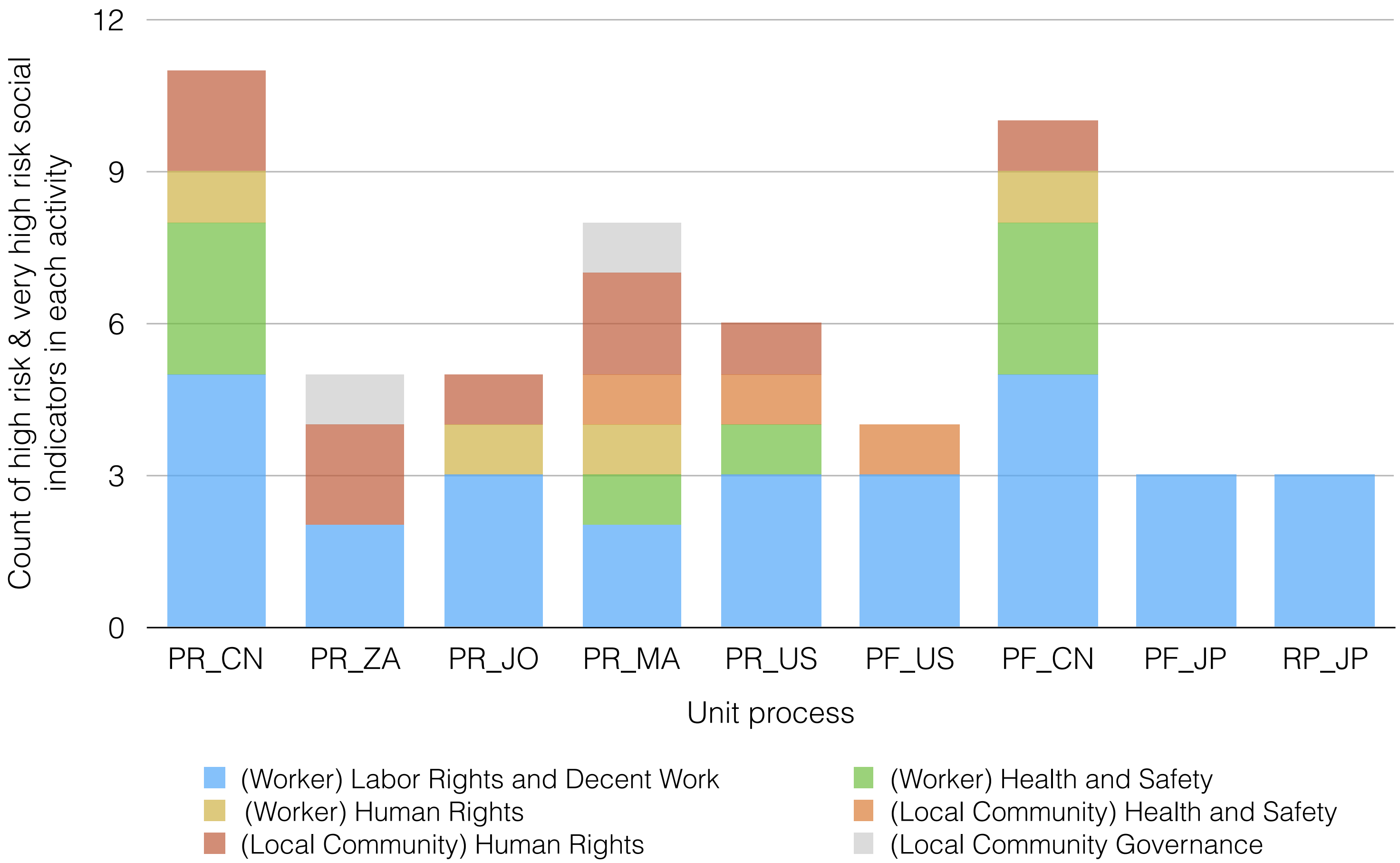

Figure 6-1. The count of high risk and very high risk social indicators in each activity that represents the hotspots activities (PR: P rocks mining, PF: P fertilizers production, RP: P recycling)

The social impact hotspots were identified as the risk of lacking the right to strike, to freedom of association, of excessive working hours, and the high risk of conflicts (Figure 6-2). The rights to strike and freedom of association were based on the universal human values first stated in the Universal Declaration of Human Rights in UN General Assembly back in 1948, where "everyone has the right to freedom of peaceful assembly and association and that no one may be compelled to belong to an association". These had been qualitatively evaluated by the International Trade Union Confederation Survey [91], along with the right to have reasonable working hours where "everyone has the right to rest and leisure, including limitation of working hours and periodic holidays with pay". However, many countries did not have data for excessive working hours. The data used were an estimation made by the SHDB based on alternative sources [83]. The risk of high conflict was defined as the clashing of interests over national values of some duration and magnitude between at least two parties determined to pursue their interests and achieve their goals based on the Heidelberg Institute for International Conflict Research [92]. In addition, the human rights of the local communities may also be violated due to conflicts in the producing countries.

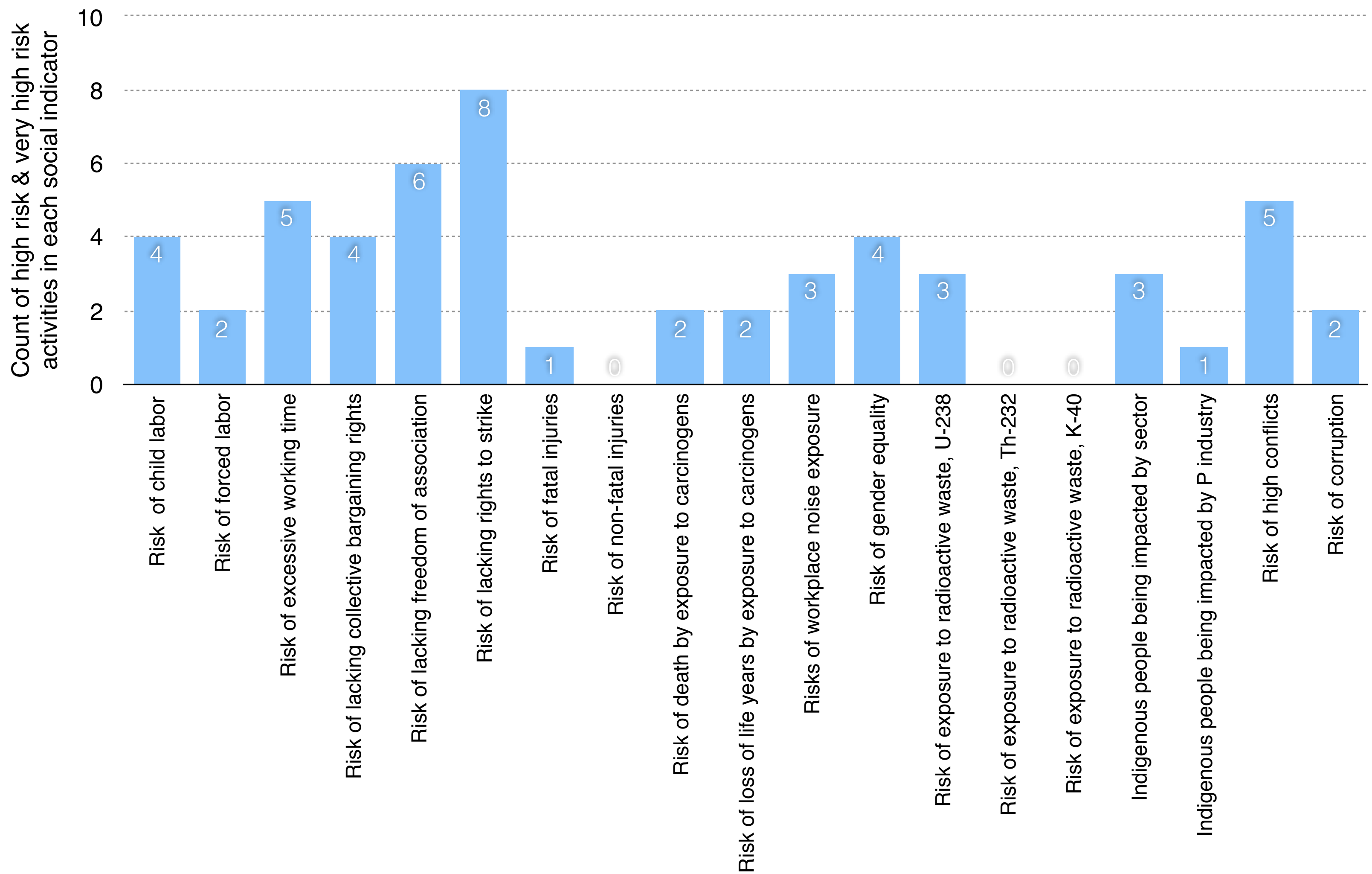

Figure 6-2. The count of high risk and very high risk activities in each social indicator that represents the hotspots social indicators.

6.2. Comparisons of mineral and recycled based P fertilizers

The results of the comparison of the social impacts of consumed mineral and recycled-based P fertilizers in Japan are presented in Figure 6-3. Figure 6-3(a) shows the comparison of fertilizers without considering the production capacity of recycled P. We showed that choosing recycled P over mineral P notably mitigated impacts on society from a consumption perspective, i.e., improving P security and commitment to sustainability. Furthermore, on the production side, the risk of social impacts on workers and local communities could be mitigated by shifting foreign-based production to domestic-based production. An exception was the worker's human rights category, which was characterized by gender equality at a workplace. Japan scored worse than the average of the foreign P producing countries.

Figure 6-3(b) shows the comparison between the current P consumption situation and the scenario of mandating P recycled from Japan, which was constrained by the maximum recycling capacity in this country. Even though switching to recycled P seemed to be promising in mitigating the social impacts (Figure 6-3(a)), the potential was less significant at the national level (Figure 6-3(b)). The differences between each social impact score were between 3–7%, except for the commitment to sustainability of society which was because the maximum recycling capacity could only substitute 15% of imported P rocks, or 7% of total P consumption. Despite the limited capacity, the nationwide implementation of P recycling would help realize a vision of a circular society in a Japanese context. Therefore, the social impact score for commitment to sustainability was much lower.

By comparing Figure 6-3(a, b), the author showed that the predominant factors for a social impact score shifted from the choice of P fertilizers to the total usage of P fertilizers. In other words, to effectively achieve lower social impacts, Japan must simultaneously promote P recycling policy and reduce the total P fertilizer consumption across the country.

Figure 6-3. The comparisons of social impact scores of (a) the consumption of mineral P and recycled P fertilizers in Japan, and (b) the current consumption of P fertilizers (mineral P) and a scenario of maximum P recycling (recycled P substitutes 15% imported P rocks). The risk levels are indicated in the scores, 0 as low risk and 3 as very high risk.

6.3. Discussions

6.3.1. Limitations

The processes included in the system boundary were limited to top-tier processes, i.e., P mining, P fertilizer production, and P recycling; and were weighted equivalently. This was done due to the lack of data to support the assessment at a national scale. For example, the resolution of data acquired from the SHDB was either at a country or sector scale, which only represented the overall situation of the whole industry, despite different types of P fertilizers. In the input-output based SLCA of fertilizers by Martinez-Blanco et al. [37], they attempted to include the second-tier process, or background processes, by using the working time weighting method based on the GaBi 5.0 database. However, they found that the available working time inventories were incomplete and insufficient to support a current detailed assessment.

Next, not all stakeholders were included in the assessment. For example, the local or central government would have to increase their spending in the case of recycled P, so such impacts were treated as a choice of public policy instead of a negative social impact. In terms of industry players, we prioritized the basic rights of workers and ignored the profitability of investors or the survivability of the companies. Some potential conflicts of interests were expected between the stakeholders. Furthermore, research and development firms were not included despite being of importance to the success of the P recycling industry.

Unlike the environmental impacts in an LCA study, social impacts may be referred to as both positive and negative. In this study, positive impacts were not included. An example of a positive impact would be the creation of further job opportunities, where the promotion of P recycling would potentially create domestic employment. In the WWTP, the recycling process was most likely to be managed by existing operators. In research and development firms, job creation could be expected. On the other hand, consuming mineral P would indirectly support jobs in foreign P producing countries.

The SLCA was sensitive to the practices in each country [53]. The supply of P rocks and P fertilizers in Japan were based on multiple import sources that varied across different years. In this study, the author used 2012 import data and considered the data for the past 15 years. As demand for P rocks and P fertilizers has decreased, the sources for P rock imports were mostly stable in terms of import ratio, and the P fertilizer imports changed with increasing trends in products from China. This assessment used the import ratio to define the activity coefficient of each production process; therefore, the assessment could be effectively updated according to the interested scenario.

6.3.2. Alternative Frameworks for Supporting P Recycling Policy

Apart from the proposed SLCA framework, other alternative frameworks applicable to support the P recycling policy have been discussed in recent publications [10, 11, 93, 94], e.g., P vulnerability, P security, and the sustainability cost of P. Initially, the debates of P addressed concerns of the long-term sustainability of P, or peak production of the mineral P [76]. However, Cordell et al. [10, 93] expanded the view by introducing P vulnerability and P security to include the geopolitical risk of P supply, the socio-economic impacts on food and the farming system, and other P issues from the perspective of a nation. These frameworks highlighted the qualitative evaluation of short and long-term risks associated with P fertilizer supply, and outlined potential quantitative indicators. Since the frameworks focused on the impacts directly related to P fertilizers, causal relationships among the activities and stressors could be depicted. For example, the impact on farmer livelihood was affected by the sensitivity to internal factors such as country dependency on P imports, and the exposure to external factors such as the international price of P rocks [93]. However, the empirical relationships between the stressors and responses are yet to be quantitatively shown.

In comparison, the social impacts evaluated in the SLCA were more generic and may not be a direct cause of P activities. For example, the presence of decent working conditions of a miner was most likely based on the culture of the mining company instead of the demand for P. The SLCA treated the indicators independently, therefore avoiding the treatment of causal linkage. However, results are considered sufficient for a consequential SLCA [64] that aimed to choose between recycled P and mineral P fertilizers. To comprehensively support a P recycling policy, the evaluation of a national P vulnerability or P security based on alternative frameworks could be complemented with the SLCA.

7. GENERAL DISCUSSION (SUSTAINABILITY ASSESSMENT)

This chapter included two parts. First, the author discussed the challenges of fitting LCA and SLCA into the LCSA framework based on the exercises conducted (Section 7.1). Second, the author outlined an alternative sustainability assessment framework—Stakeholders-Centered Approach—that is worth of future study (Section 7.2).

7.1. Challenges of fitting LCA and SLCA into LCSA framework

This work was initially motivated to develop and examine an integrated LCSA framework. Based on the framework of Guinee et al. framework [40], the author showed the component of environmental (Objective 1) and social impact analysis (Objective 2) in Figure 7-1. However, the two components were eventually performed separately and not integrated due to technical difficulties. Some of the challenges of fitting LCA and SLCA into the LCSA framework were discussed.

First was the issue of harmonizing the functional unit. The functional unit of LCA was defined as 1 kg of P content in a P fertilizer product (SSP, FP, MAP, or HAP), and thus the incremental environmental impact could be quantitatively measured. However, the functional unit of SLCA was defined as consuming an option of P fertilizer types (mineral or recycled P) based on the combined set of P sources in a country; the social impact was semi-quantitatively measured to show the relative differences of the two options, instead of measuring the absolute social impact of one activity. Therefore, the two components were not ready for aggregation.

Second was the issue of system boundary consistency. LCA was a product and process based assessment, therefore it was able to upscale to meso-level to match the scope of SLCA. However, as discussed in Chapter 6, SLCA lacks of a granular dataset to address most of its economic flow—only primary production processes were assessed. Therefore, the current SLCA was incapable to match the system boundary of LCA or CLAC.

Apart from the above technical challenges mentioned above, a fundamental issue was what kind of impacts to be measured or prioritized in sustainability assessment. As the work in LCA and

SLCA was to some extent driven by data/indicator availability, a clear limitation was the lack of qualitative analysis to reflect the stakeholders' concerns. Therefore, a potential for future study is discussed in the next section.

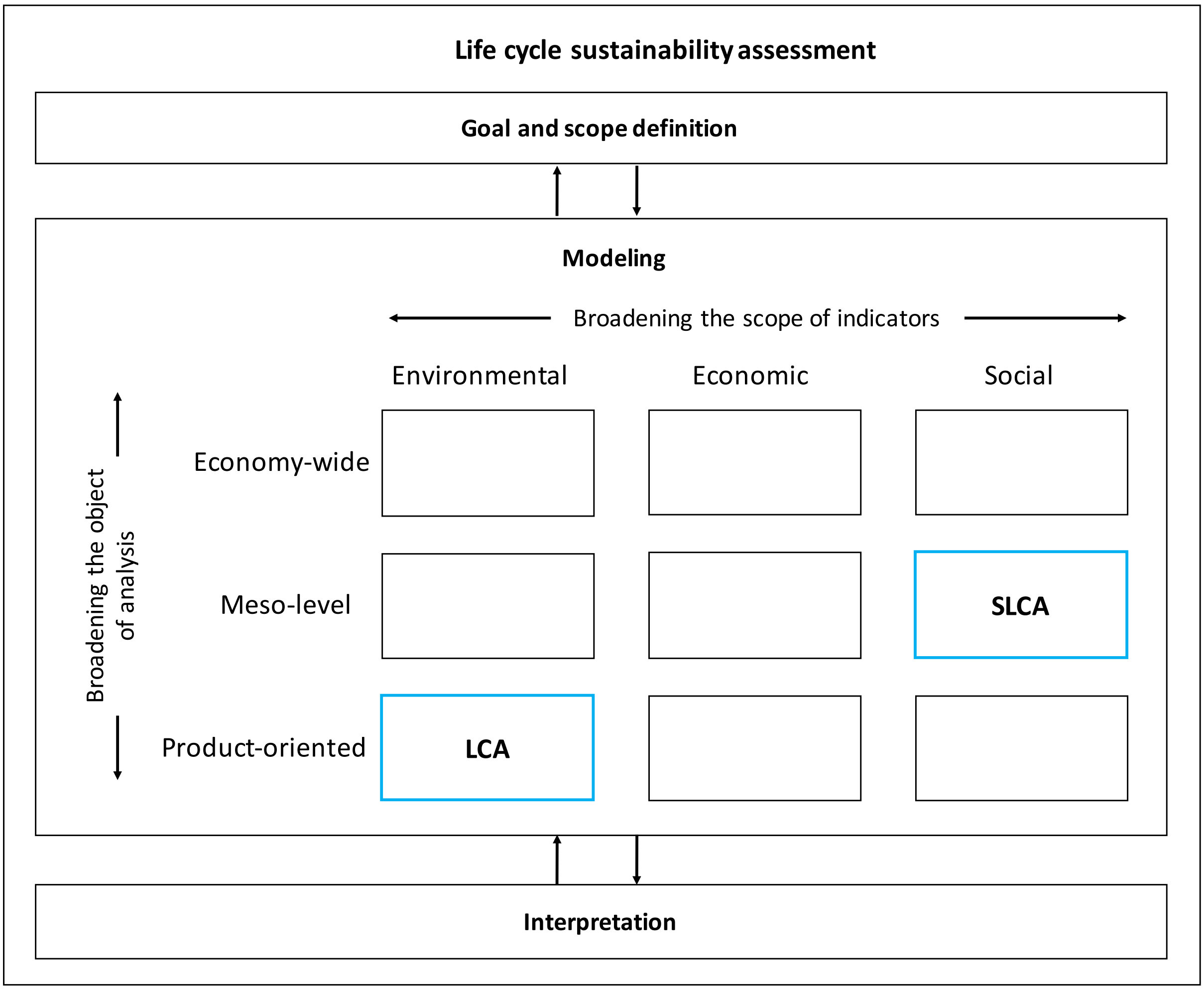

Figure 7-1. Fitting the conducted LCA and SLCA into the LCSA framework.

7.2. Suggestion of sustainability assessment framework with stakeholders-centered approach

As of LCA, LCSA under current discussion would be a data-driven approach. However, in sustainability science, apart from collecting quantitative data, the involvement of actors from outside academia into the research process in order to integrate the best available knowledge, reconcile values and preferences, as well as create ownership for problems and solution options, were important [95]. This is often termed as transdisciplinary [95-97]. In the case of this thesis, although SLCA addressed the impact on stakeholders along P supply chain, stakeholders' opinion was not directly reflected in the assessment. For example, in the labor rights assessment, excessive working hours might not necessary be a negative impact if a longer working hour was desired for workers to improve their livelihood.

To address insufficiency of LCA approach mentioned above, specifically in engaging stakeholders and incorporating stakeholders' opinion, the author outlined an alternative sustainability assessment framework—stakeholders-centered approach—that is worth of future study. The stakeholder-centered approach, or participatory, was to identify intervention points for promoting sustainable P consumption based on stakeholders' motivation, interests, and viewpoints (Section 7.2.1 and 7.2.2). The outline was an original interpretative result of a panel discussion during the 5th Sustainable Phosphorus Summit, August 2016.

The Sustainable Phosphorus Summit was a series of international conferences that focused on multidisciplinary aspects of P. Scientists and stakeholders were brought together to define the global research priority agenda, integrating P-related issues across scales, geographical regions and scientific domains. The author participated in the 5th conference in Kunming, China [87]. During the conference, the special panel discussion on P governance was hosted by Dana Cordell, a scientist from University of Technology Sydney, and Arnoud Passenier, a policymaker from the Ministry of Environment, Netherland. Contributors from the academic included Stuart White (University of Technology Sydney), Jianchu Xu (Chinese Agricultural University), Gang Pan (Chinese Academic of Sciences), Oene Oenema (Wageningen University), Susanne Schmidt (The University of Queensland), Fusuo Zhang (Chinese

Agricultural University); and from the industry included Michel Prud'Homme (International Fertilizer Organization) and Ludwig Hermann (Outotec Germany); and from the international organization, Debra Turner (UNFAO).

7.2.1. Stakeholders' motivation, interests, and viewpoints

Governing the P value chain for food security, livelihood, and environmental integrity needs the joint efforts from all stakeholders—scientists, policymakers (national and international), industry players, and farmers. However, the current unsatisfying progress in P pollution control and P resource management have highlighted the communication gaps between the stakeholders, and the need for a better understanding.

P is a demand-based industry. The core stakeholders in the supply chain are therefore the consumers or farmers and the fertilizer industry players. In addition, policymakers have the power to regulate P practices for ensuring environmental integrity and food security, especially when market failure happened. Scientists, who are funded by government or industry, support the decision making of P policy and the technology development in P industry through research activities and the creation of knowledge.

Although the stakeholders are clearly dependent on each other, their motivation, interest, and viewpoint on P sustainability issues are diverse and often inconsistent with each other. Subsequently, these differences may deter the collaboration among the stakeholders. Based on the panel discussion, The stakeholders' motivation, interests, and viewpoints on P sustainability issue were summarized in Table 7-1. The results showed a generic situation that was related to experts' experiential knowledge and non-specific to particular local context.

Some examples of mismatch in stakeholder's interests were discussed below.

- Scientists vs. Policymakers

  Even though scientists and policymakers are supposed to be the third parties to jointly promote the transformation to sustainable P supply, they have very different interests. Driven by curiosity, scientists focus more on long term issues, but policymakers are keener on immediate problem. Therefore, a scientifically sounds proposal might not necessarily be appealing to the policy support.

- Industry players vs. Farmers

  Fertilizer industry has the capacity to produce greener and more specific type of fertilizer for the best practice of agriculture, such as struvite fertilizer. However, the prerequisite is sufficient demand from the farmers. Traditionally, farmers are led to believe that, more fertilizer equal to more yield; therefore, the preventing the penetration of technological innovation from the industry.

Table 7-1. Summary of stakeholder's motivation, interests, and viewpoints on P sustainability issue.

Stakeholder	**Motivation**	**Interests**	**Viewpoints on P Sustainability Issues**
Scientists	Pursuit of knowledge, curiosity driven	- Long-term P sustainability - Detail analysis - Uncertainty analysis	- P is a wicked problem, unlike environmental problem such as ozone depletion, there is no single solution. - Current P impact is the result of market failure. - Industry should solve the problem themselves (if possible) while government must lead in clarifying priorities and responsibilities. - Scientists have more solutions to offer if being delegated appropriately.
Policymakers	Pride in problem solving, result driven	- Short-term and/or immediate problem - Solution-oriented suggestion - Risk-adverse (non-controversial) action - Networking with stakeholders	*National government* - Prefer face-to-face roundtable discussion over reading lengthy reports. - P technological solution is easier to initiate by industry instead of government. *International government (FAO)* - Prioritize nutrient management that only include P as part of the agenda. - Act as "broker" to bridge science and policy.
Industry players	Sustainable business, profit driven	- Current market demand - Creating market demand (green fertilizer) - Cost of P fertilizer products - P mining and processing efficiency	- Industry plays vital role in controlling the whole P supply chain. - Innovation in communicating greener fertilizer products to farmers is essential. - Niche market for specific fertilizer is good but hard to scale up to be profitable. - R&D to create knowledge is outsourced to academics, but industry create value from the knowledge.
Farmers and food consumers	Crop yield, cost driven	- Price of fertilizers - Quality of fertilizers	- Believe in "more fertilizer more yield", especially in less educated rural community

	- Change in farming practice	- Consumer has growing sustainability awareness in product choice.

7.2.2. Mapping the intervention points for a better stakeholders' engagement

To achieve better stakeholders' engagement, improvement of the stakeholder relationship is needed. The author identified seven key intervention points based on the interpretation of the panel discussion, which were mapped according to the relationship with stakeholders in Figure 7-2.

The intervention points to reengage stakeholders were briefly described below. The interpretative result was not meant to be complete. Instead, it reflected the contemporary concerns and the priority actions based on the expert opinions.

A. *Communication and trust building*

The International Fertilizer Industry Association is emphasizing on innovation in communication with downstream stakeholders, including retailers and farmers, to introduce new or greener fertilizer types. Farmers in general are reluctant to change because they do not trust new technology. The industry has the burden to proof. In some cases, irresponsible retailers would sell low grade sands to mix with high quality fertilizers to increase their profits, therefore damaging the trust between the fertilizers industry and farmers. To bring back the confident to farmers, the industry is working on training fertilizer advisors to directly engage the farmers.

B. *Bonus merit system*

Farmers can be incentivized to improve their P use practices through the choices of fertilizers. In the Netherlands, there are cases where communities put in an additional monetary value to milk production, that obtains higher sustainability performance, thus creating a win-win situation. Innovation in the value chain can reform the agricultural market. A society need longer time for big producer to make the changes, although a local case study has proved to be viable.

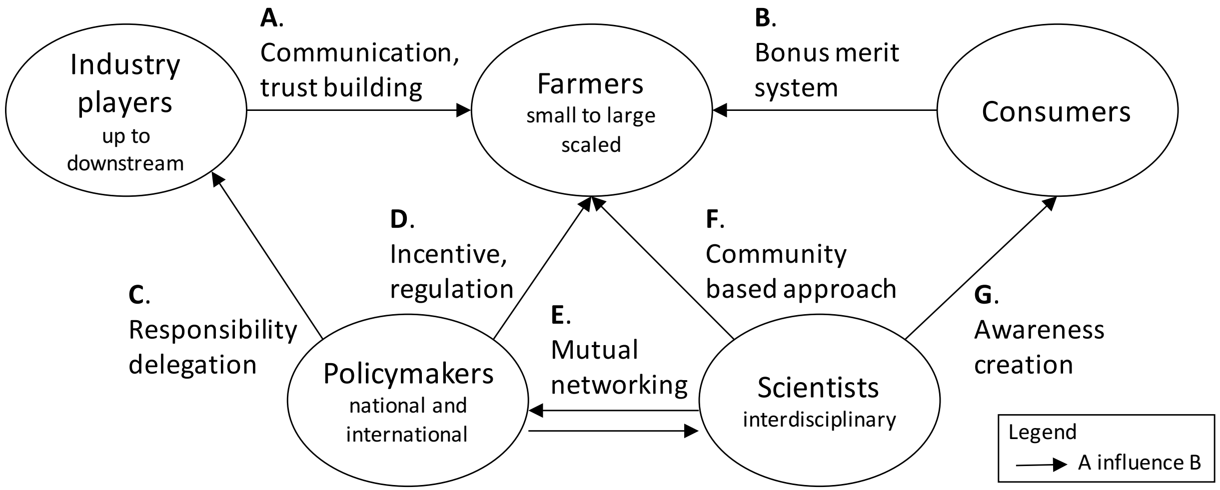

Figure 7-2. Seven key intervention points for better stakeholder engagement based on the panel discussion.

C. Delegation of responsibility

Although a society cannot depend on governments to initiate full strategies for P sustainability, governments must play the leadership role in delegating responsibility. First, governments should repackage the holistic P problem into specific small topics that are manageable. Then, governments shall define the urgency and priority of each topic, and clarify the scope of government intervention and the responsibility of the associated industry. Sharing a clear scope of responsibility will allow industry to tackle their own problems.

D. Incentive, regulation, and education

Current P impacts on the environment is the result of market failure, therefore immediate action on institution arrangement must be emphasized. Government shall strengthen the application of fertilizer regulations, provide market instrument to promote environmentally friendly practices and promote awareness through education. A survey of Chinese farmers has found that, most rural farmers have no knowledge on fertilizer application and lack of ecosystem mindset; they believe more fertilizers will return higher yield. To kick start the change, reducing fertilizer use or using green fertilizers, funding for especially poorer farmers is necessary to guarantee them the potential payback gap, and to help them improve practices. For corporate farmer, market instruments like P trading and tax on P are currently unavailable.

E. Mutual collaboration and networking

Networking between scientists and policymakers through conferences, workshops, and other activities brings mutual benefits. Today, policymakers are having less capacity to promote research activity due to the limited staffs. Attending conference like Phosphorus Summit is an effective alternative to understand the overall status in a short time with a limited investment of funds. Active personal networking has to be encouraged. Also, a specific coordinator and/or specific communication channel towards the academic community is proposed. An example of lack of commutation is shown in the Tiananmen Square Military March in 2015, where the Beijing air pollution was cleaned up with strong policy intervention, such as shutting down factories temporarily, but the waterbodies surrounding the square were left polluted with algae bloom. The perception of untreatable algae bloom shows the disconnect between the government and scientist community.

F. *Community based approach*

There is no one-size-fits-all solution for solving P problems. Understanding the local context is needed to provide sustainable solution. A negative case study is shown in Chinese pig farming. To prevent high P effluent from pig manure, regulation on constructing on-site wastewater treatment plants was enforced. However, the policy was in favor of big corporate farmers, while small scaled household farmers were eliminated due to being incapable of upgrading their processes. Thus, the policy has indirectly widened social inequality.

G. *Awareness creation*

Transdisciplinary scientists must translate scientific knowledge on P sustainability into public friendly knowledge to create awareness. In the case of China, the country is rich in P resource but poor in P knowledge. A recent policy in water pollution and P control, reducing P input by 2020, was initiated by President Xi Jinping, becoming aware of a Science publication on P status in China. A strong top-down enforcement subsequently accelerated nationwide P mitigating actions.

According to the stakeholder-centered approach, the case of Japan should be further studied. From the experiences of this work, a beginning point can be the P Recycling Council that was chaired by Dr. Hisao Ohtake of Waseda University. The council is an active domestic platform for communication among the scholars, industry partners, and policymakers.

8. CONCLUSION

Recycling P from municipal wastewater is one of the key issues to promote sustainable consumption and production of P fertilizers. The challenge involves a transformation from the consumption of mineral P to recycled P, which can be accelerated with the implementation. To counter the perception of the costliness of Recycling P investment, a life cycle thinking is important to assist policymakers in understanding the full extent of external benefits that are associated with the transformation, or the external cost of current unsustainable practice. In such context, this thesis provided some analysis that are lacking in previous studies on modeling the impacts of P fertilizers. Considering the triple bottom lines of sustainability, this thesis analyzed the environmental and social impacts along the life cycle of P fertilizers.

In Objective 1, the production of recycled P fertilizer in the form of MAP was proven to be environmentally friendlier than mineral P fertilizers in the case of Japan. The assessment was based on the comparison to HAP, SSP, and FP in GWP and eutrophication potential. In particular, a CLCA modeling method, which accounted the consequential effects of introducing the recycled P technology, was applied in the assessment. In contrast to conventional ALCA, the author showed that CLCA could drastically change evaluation results, as the predominant factors for GWP and eutrophication potential on recycled P production were the coagulant use in the avoided P removal process, and the effect of reducing P effluent from WWTP respectively. Such CLCA framework for MAP production is generalizable and applicable to other sites of studies, as long as information on local wastewater treatment method is up to date. For policy recommendation, based on the external cost estimation of environmental impacts, the author showed that the most effective solution for promoting transformation of P fertilizers consumption was replacing FP with MAP. This was also supported by the similarity of agronomic characteristic and thus the market of P fertilizers in Japan.

In Objective 2, the author contrasted the potential social impacts of consuming mineral P and recycled P in the case of Japan, and showed that recycled P would have relatively smaller impacts on the stakeholders at various phases of the P supply chain. An original SLCA framework to perform comparative study was developed. The social impacts were summarized into seven broad stakeholder-impact categories–worker's labor rights and decent work, health and safety, and human rights; local community's health and safety, human rights, and governance; society's P security, and commitment to sustainability—based on the 24 indicators. Specific P-related indicators were proposed in the assessment framework. Social impacts factors included the origin of country of the P products, and the practices in the country. The author showed that, even though the marginal social impacts of mineral and recycled P fertilizers were significantly different, the normalized social impacts were almost insignificant, as the maximum production capacity of recycled P from WWTP in Japan was only able to substitute about 15% P rock import. Social hotspots activities were identified as mining in China and Morocco, and manufacturing in China, and included the risk of violating worker's labor rights and decent work, and the risk of impacts on local community's governance. Although the SLCA was constrained by the data availability, the SLCA framework was reasonably useful in organizing and evaluating the vast scope of social impacts.

To realize a sustainable consumption and production of P fertilizers, the current thesis could not achieve integrated LCSA framework due to the limitation of harmonizing the functional units of LCA and SLCA, and the inconsistency of system boundaries. Also, apart from the results of LCA and SLCA, this thesis was lacking a critical aspect of sustainability in transdisciplinary perspective—a qualitative analysis on stakeholder's motivation, interests, and viewpoints on sustainability. To supplement the analysis, a stakeholder-centered approach, which was developed based on a panel discussion of leading P experts, was suggested as a theme for future study.

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