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Circular Economy for Phosphorus Supply Chain and its Impact on Social Sustainable Development Goals

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ABSTRACT

To be able to grow crops, we have interfered with Earth's reserves of one of top three essential elements, phosphorus (P), as to which we face a problem related to its high consumption compared to available resources. This forces us to follow the alternative of closing the phosphorus loop from a circular economy perspective. However, there is a lack of research on regional and global social sustainability in this area, as emphasized in the United Nations' Agenda 2030 goals for sustainable development. In this paper, we address social challenges involved in global phosphorus supply chain, such as eradicating poverty, child labor and malnutrition; promoting gender equality; providing decent work and economic growth; maintaining sustainable water use; and achieving food security. Our research is driven by the question of whether the circular economy aims to direct phosphorus management towards tackling social issues associated with its supply chain. We use system dynamics modelling by combining the concept of material flow analysis and social life cycle assessment. Detailed analysis at regional and global levels indicates a paradoxical social impact of phosphorus circular model. This reflects the multiple stakeholders involved, and the regional interactions with phosphorus circular economy transitions. Improvements can be demonstrated in reducing poverty and providing safer work environment in many regions, e.g., Western Asia (93%), New Zealand, Central Asia, and Europe (44-61%), while achieving employment targets is limited in Northern and Eastern Europe. Circular model fails to promote gender equality, it also exacerbates exploitative child work problem for the Caribbean and most Africa. It provides sufficient nutrition to North America, Australia/New Zealand, and Northern Europe. It achieves water use targets in several regions with 53% savings worldwide. Finally, circular model contributes to P efficiency (average balance of 1.21 kgP/ha) and strengthens P security within most regions with an average of 64%.

Keywords: Critical materials; phosphorus; social sustainability; circular economy; dynamic modelling

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1. Introduction

To meet our demand for food, we have moved large amounts of phosphorus (P), the third element in Earth's reserves, to fields, rivers, and forests, devastating the ecosystems. Our world has been evolving with global population growing in numbers and changes in lifestyles leading to increases in consumption of critical materials such as phosphorus. The criticality assessments of raw materials differ as they are conducted at different scales, e.g., institutional, regional and global, as well as take into account indicators related to multiple aspects, e.g. social, geological, environmental, technological, and geopolitical (Schrijvers et al., 2020). Hence, there are variations in the outcomes of critical material identification (Frenzel et al., 2017). Supply risk, vulnerability to supply restrictions and economic importance are all common characteristics of critical raw materials (European Commission, 2018a; Graedel et al., 2015). Phosphorus has been identified as a significant critical material according to several assessments (European Commission, 2020a; Golroudbary et al., 2019a). Phosphorus plays a prominent role in our food chain, has no potential substitutes, and its primary source – phosphate rock – is finite and can only be found in a few countries. As a result, we have been facing various challenges such as resource scarcity and food insecurity. Many of the world's food producers are in danger of becoming completely dependent on trade with a handful of countries - phosphorus suppliers such as China, Morocco and Western Sahara, United States, Russia, Jordan and Brazil (Golroudbary et al., 2019a).

Solutions to these problems lie in recapturing and recycling phosphorus, moving it from where there is too much to where there is too little of it, and developing ways to use it more efficiently. Therefore, the concept of circular economy has emerged to sustain the conservation of phosphorus within the supply chain. A circular economy is meant for the conservation of material's value within the economic system as long as possible (European Commission, 2020b). This concept serves the mitigation of phosphorus criticality, as it aims to extend the useful life of raw materials extracted from the environment (Gaustad et al., 2018).

Cordell et al.(2013) estimated the peak of global phosphorus production to be reached in 2030 and Golroudbary et al.(2019b) expect the peak of energy consumption and greenhouse gas emissions for phosphorus supply chain to occur in 2034. Those findings laid the foundations for the analysis of the rationality of using phosphorus recycling in line with the circular economy in Europe by Golroudbary et al. (2020). Following this line of thinking, the concept of circular economy including the integration of the socioeconomic system, is mainly introduced to deal with a series of challenges including waste generation, resource scarcity, and sustained economic benefits. Circular economy is a model meant to decouple the social benefits and human wellbeing from resource use, production, and consumption (Van Hoof et al., 2018). It is believed that circular economy may help in finding answers and solutions to the ongoing societal challenges and bringing opportunities for sustainable growth (Niskanen et al., 2020), e.g. a transition to a circular economy is expected to raise employment by between 300,000 and 1 million employees in five European countries: Finland, France, the Netherlands, Spain, and Sweden (Moreau et al., 2017; Wijkman and Skånberg, 2016).

The degree to which the circular economy approach has been implemented for phosphorus chains differs across countries as it is based on national policy and depends on aspects such as environmental impact, economic benefits, and resource scarcity (Golroudbary et al., 2020). Bernhardt et al. (2018) demonstrated that a successful transition to circular economy for phosphorus starts by blocking the lost channels and utilizing wastes derived from mining, beneficiating, and production processes. Other studies have also shed light on several factors such as addressing social acceptance (de Boer et al., 2018), creating market niche for waste derived from P fertilizers (Nättorp et al., 2019), improving recovery technologies (Egle et al., 2016), increasing recovered phosphorus production capacities (Jedelhauser and Binder, 2018), and updating the legal limitations that restrict the advancement in P recovery (Barquet et al., 2020) and the use of waste-derived products (Mehr et al., 2018). This diversity of aspects meant to be improved by phosphorus circularity calls for different measurement tools or different sets of measurement indicators (Moraga et al., 2019).

While the idea of phosphorus circular economy emphasizes sustainable development of multiple regions, equally important sustainability indicators which represent social and ecological values are often disregarded or ignored. Therefore, the promising achievements on the social sustainability side are still questionable. There is a large gap between social indicators for different nations, and the social threshold yet to be met by many countries. Hence, circular economy also faces a lot of criticism mainly because it disregards social equity and goals (Niskanen et al., 2020).

The central driver for the circular economy is the reduction or displacement of primary production. However, continuous production of a secondary material might bring its price down and thus increase the overall demand leading to a rebound effect in which primary production is reconsidered. As a result, it may lead to material and

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energy intensive production systems (Zink and Geyer, 2017). While the major focus of phosphorus management is on displacing primary production with recycled material, the demand for energy from recycling processes is often overlooked (Cullen, 2017). In addition, several studies have shown that excess phosphorus is leading to social and environmental damages, and therefore they suggested urgent need of recycling in line with the circular economy model (Mayer et al., 2016; Takasugi et al., 2020). This requires a comprehensive understanding of P-related costs and benefits to ecosystems and society.

The world is facing a list of social challenges including poverty, inequality, and resource insecurity (FAO, 2020a; United Nations, 2020a). Despite the modest improvement achieved in 2019 – 8.8% of global population under the poverty line in comparison to 10% in 2015, the rate of poverty reduction slowed down (United Nations, 2020a). In 2016, over 150 million children worldwide were victims of child labor (ILO, 2017), out of which 70% were engaged in the agriculture sector (FAO, 2020b). Employment growth has declined by around 4% during the last decade (ILO, 2020; World bank, 2020a). Other social challenges affect directly human basic needs. The use of freshwater is growing and there is a global concern about water scarcity. Water scarcity affects up to 40% of the global population (UNDP, 2020). The decline in soil fertility as well as the unsustainable water use prevent the continuous supply of food (FAO, 2013). Food insecurity is becoming a growing issue as the world population grows and many regions experience the lack of substantial phosphorus reserves (Cordell et al., 2011).

Considering these global issues, this paper provides an insight into the major question: Does a circular economy contribute to the achievement of the social sustainable development goals associated with phosphorus supply chain? We are also concerned about the trend which transition to a circular economy creates within the phosphorus management. This is where our research strives to find out whether the circular economy pushes the phosphorus management forward to present a better alternative compared with the linear economy.

This study tries to answer those questions by examining the effect of the circular economy on the phosphorus chain and its contribution to the accomplishment of social sustainable development goals. We respond to the call of the UN to achieve the sustainable development goals (SDG) addressed by the United Nations (United Nations, 2019).

2. Materials and methods

In this study, we propose a dynamic model based on system dynamics (SD) methodology introduced by Forrester (1997) by combining the concept of two other methods including material flow analysis (MFA) and social life cycle assessment (SLCA). The significance of this combination lies in the ability to quantify mass flows and assess social consequences within a holistic system considering the dynamic behavior and interaction of multiple parameters of global phosphorus supply chain over time. We believe that this type of dynamic modeling creates a bridge between MFA and SLCA research, as it allows researchers from both fields to tackle new research questions with unprecedented comprehensiveness.

The MFA method is used as a framework for systematic assessment of flows and stocks of phosphorus at local and global scale. All stages of the supply chain including mining, processing, production, and recycling are considered in this study. The steps of extraction, manufacturing, loss, storage, stocks, input and output flows, use and disposal of global phosphorus supply chain are analyzed. The development of MFA goes back to the 1990's and early 2000's when it was used by different research groups and for multiple purposes, with central publications (Brunner and Rechberger, 2016; Van der Voet et al., 2002). MFA views the supply chain as a system composed of P flows and stocks and assesses them systematically (Brunner and Rechberger, 2016). Various studies have used the MFA to quantify phosphorus input and output flows in certain sub-stages and in the whole supply chain. Previous studies include quantitative analysis of phosphorus flows at regional (Chowdhury et al., 2016), national (Cooper and Carliell-Marquet, 2013), continental (Jedelhauser and Binder, 2015), and global scale (Chen and Graedel, 2016).

Assessing the social impact of life cycles has been developing for around 30 years. Fava et al. (1993) introduced the concept of the social welfare impact category. Their proposal built on an idea of widening the discussion to include the social impact category into the life cycle assessment of products and systems (Benoît et al., 2010). SLCA sheds light on the social aspects of product life cycles. It is one of useful methods of examining social impacts and, if possible, suggesting improvements (Benoît et al., 2010). Several research studies deployed this methodology to measure the social impact of products (Foolmaun and Ramjeeawon, 2013), systems (García-Sánchez and Güereca, 2019), and technologies (Lehmann et al., 2013). There is no general agreement as to which indicators should be considered to measure social impacts, partly due to the lack of sufficient literature on the topic and partly due to the difficulty to grasp social sustainability, as notions underpinning the concept are often subjective (Ahi and Searcy, 2015). However, it is almost agreed that indicators should be measurable and possible to assess (Popovic et al.,

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2018). This study follows the UNEP (2020) guidelines for the social LCA. One tonne of phosphorus is the functional unit considered throughout the calculation process. The impact pathway assessment method (IPS S-LCIA) was adopted to analyze the social consequences of the phosphorus life cycle. The study aims at analyzing the social impact in the context of the SDG's of the UN. Therefore, we consider the associated SDG indicators in the model to be at the end of the cause-effect chain (endpoint impacts). Data sources include ILO (2015), ILOSTAT (2020a, 2020b, 2020c, 2020d, 2020e, 2020f), World bank (2020b, 2020c, 2020d, 2020e), FAO (2020c, 2020b, 2017).

To manage phosphorus sustainably, we clearly need an accurate understanding of where P is stored (i.e., stocks) and how it moves through the system (i.e., flows), as well as how the different variables (i.e., social factors) influence the system and contribute to the specificity of the behaviour of each part of the supply chain over time. System dynamics modeling is used to study the behavior of complex (many objects interact with one another), interactive (variables' interaction produces the distinctive behavior of the system) and dynamic (distinctive behavior of the system varies over time) systems within changeable conditions. Also, system dynamics is capable of offering several advantages, as it (i) estimates and forecasts future behaviors and trends of a system (Torres et al., 2017), (ii) considers and understands the interrelated behavior and the causal relationship between the different parameters and variables in the system (Golroudbary and Zahraee, 2015; Sterman et al., 2015), and (iii) analyzes multi-systems given their established relationships (Jia et al., 2021). Several studies used SD methodology to examine the dynamic interactions among multiple parameters in the phosphorus supply chain such as mass flows in food chain (Treadwell et al., 2018), solid waste management (Kollikkathara et al., 2010), and environmental consequences of phosphorus supply chain (Golroudbary et al., 2019a). Using system dynamics, this study analyzes the social impact of phosphorus circularity in the context of the sustainable development goals. For this, the concept of MFA is used to quantify phosphorus flows through its life cycle and the concept of SLCA is used to determine the social impact of linear and circular phosphorus as input for SD model. Besides, several exogenous variables such as populations, consumption patterns and recycling technologies are considered in the SD model. Figure 1 shows details of the phosphorus model and data sources.

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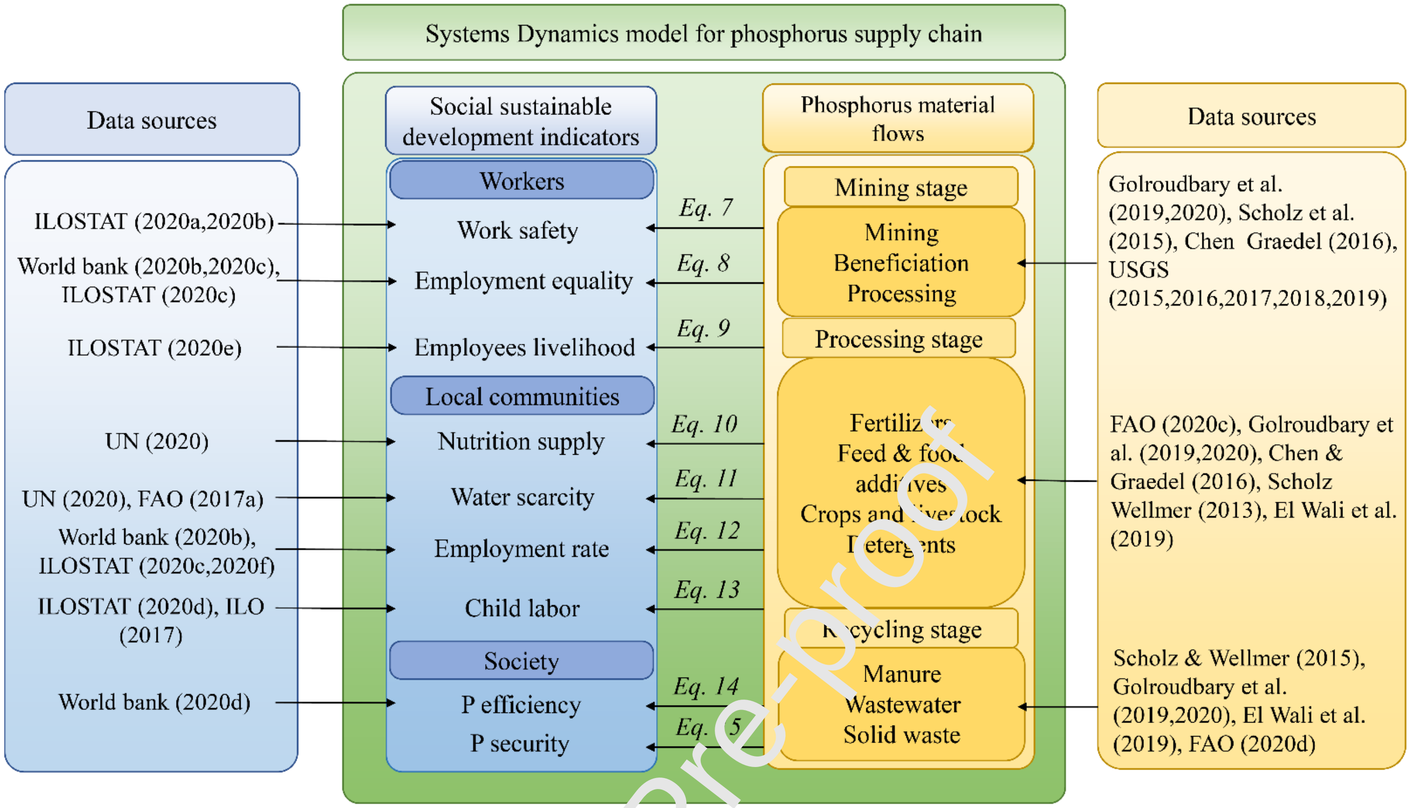

Figure 1. Conceptual framework of the proposed phosphorus model.

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Dynamic model of the linear and circular phosphorus

The system boundary in this study as shown in Figure 2 consists of two sub-systems including (1) phosphorus mass flow characterised by its supply chain; (2) social impact sub-system characterised by the list of social indicators. In this study we analyze 161 countries. The list of countries is presented in Annex (Table B.1). Phosphorus flows through three major steps. The first step is the industrial stage corresponding to the mining of phosphate ores, followed by the beneficiation and the processing into phosphoric acid. The second step covers the production stage, where phosphorus is included in tradable commodities including fertilizers, food and feed additives, laundry detergents, and other industrial uses. The fertilizers are then used in agricultural production of crops such as: rice, wheat, barley, sorghum, millet, rye, oats, potatoes, sweet potatoes, cassava, soybeans, beans, peas, rapeseed, olive, sugar beet, sugar cane, seed cotton, vegetable, and fruits. On the other hand, feed additives are used for livestock production of the following species: sheep, goats, horses, cattle, buffaloes, mules, pigs, ducks, chickens, geese, and turkeys. The third step is the dissipation and recycling of phosphorus following the consumption stage. This study addresses the consumption stage, i.e., human consumption of foods of animal and vegetable origin. The dissipation of phosphorus takes place in the form of losses across the supply chain. Losses begin already at the mining and beneficiating phase. In the agricultural production phase, large amounts of phosphorus are lost to the marine systems from soil, due to soil loss, leaching, runoff, and erosion. The recycling phase of phosphorus covers the three streams including manure, wastewater, and solid waste. Manure is by far the largest source of recycled phosphorus for fertilizer applications. The sources of manure considered in this work originate from the following livestock species: donkeys, cattle, buffaloes, chickens, ducks, mules, sheep, goats, and pigs. Wastewater is a supplementary source of fertilizers and is also seen as an opportunity for the reduction of water eutrophication process as well. It originates mainly from human excreta, detergents, and other industrial waste. Solid waste is generated by human and livestock consumption. All these flows of waste are immediately treated before they are either recycled or landfilled.

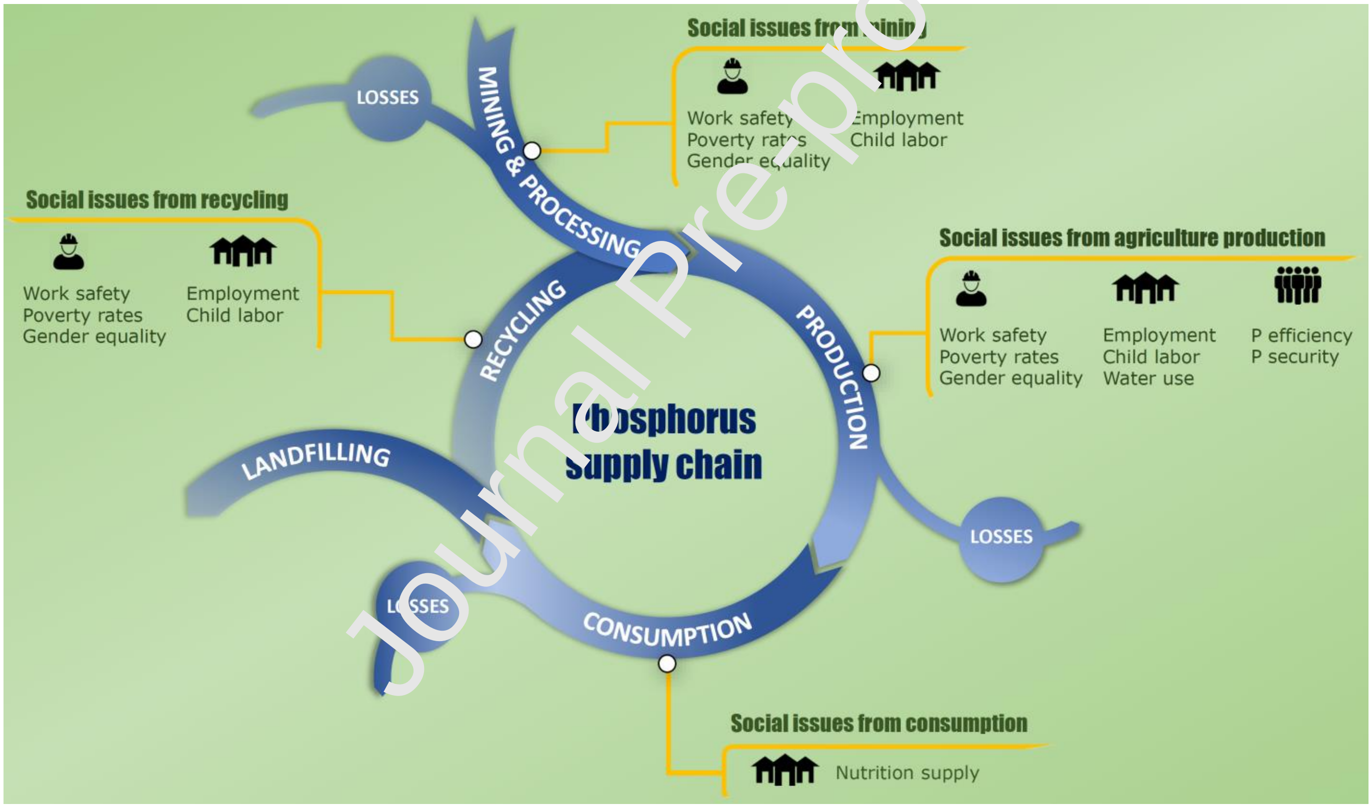

Figure 2. Conceptual model of the phosphorus supply chain and its social sustainable development impact.

External economic activities were also included in the system of material trading (imports and exports). Material trading takes place in the pre-consumption stages (mining and production), where phosphorus is traded in

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the form of refined phosphate rocks from the mining stage, phosphoric acid from the material processing stage, phosphate fertilizers, feed and food additives from the production stage.

Stocks and flows are the foundations of the system dynamics modelling. The dynamic behaviour of fertilizer stock in period $t - t_0$ is given as a time integral of net flow rates to and from the stock ($FS(t)$).

$$FS(t) = \int_{t0}^{t} \left(P_f(t) + \Delta I_f(t) + R(t) - \ Cr(t) - \ PL_f(t) \right) dt + FS(t_0) \qquad (1)$$

Where the inflow variables represent the fertilizers production rate, $P_f(t)$; the net fertilizers imports, $\Delta I_f(t)$; the rate of fertilizers from recycling, $R(t)$; the outflow variables represent crops production, $Cr(t)$; phosphorus loss from the soil, $PL_f(t)$; and the initial amount of fertilizers in stock, $FS(t_0)$. Material flow variables are subject to change based on the dynamics of their stock source. For instance, the mathematical formula for crop production is as follows:

$$Cr(t) = V(t) \times FS(t) \qquad (2)$$

Crop production rate depends on the amount of fertilizers available in its stock on annual basis. This dependence is reflected in the exogenous variable $V(t)$ in time t, representing the production coefficient $Cr(t)$, whose value ranges between 0 and 1. The detailed list of variables, as well as their formulas and data used to calculate them can be found in Supplementary Information A.

This study looks at the linear and circular economy models in the phosphorus supply chain. Circular flows represent the P input into the agricultural production sector from the recycling of manure, wastewater, and solid waste. Linear flows, on the other hand, represent the P input into the same sector originating from mining and net imports. Our analysis considers different origins (sources) of P used for agricultural production (circular and linear). Linear sources provide the primary flows to the phosphorus supply chain. Circular sources provide secondary flows to the phosphorus supply chain in the context of a circular economy. The proportions of circular $\left(P_C(t)\right)$ and linear phosphorus $\left(P_L(t)\right)$ within the agricultural production sector is determined through the following equations:

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$$P_C(t) = \frac{\sum_{c=1}^{3} C_c(t)}{\sum_{c=1}^{3} C_c(t) + \sum_{l=1}^{3} L_l(t)} \tag{3}$$

$$P_L(t) = \frac{\sum_{l=1}^{3} L_l(t)}{\sum_{c=1}^{3} C_c(t) + \sum_{l=1}^{3} L_l(t)} \tag{4}$$

where $C_c(t)$ is the annual amount of circular phosphorus from source $c = 1, 2, 3$ (manure, wastewater, and solid waste); and $L_l(t)$ is the amount of linear phosphorus from source $l = 1, 2, 3$ (production of fertilizers and additives, and net imports).

Circular economy models are identified at three levels: micro, meso and macro (Ghisellini et al., 2016). This study focuses on the phosphorus circular economy at global and national levels, i.e., it corresponds to the macro level. The main circular economy indicators for the phosphorus supply chain are presented as follows:

- Domestic material consumption (DMC): The calculation of phosphorus footprint is important to track the flows of material within and across the national borders of countries. This includes by necessity indirect flows and resource requirements. However, scarcity of data prevents such in-depth analysis at a country level. This study uses the domestic material consumption (DMC) to calculate the amount of phosphorus required to enter the economic system. DMC equals the total amount of material used to meet the demand for goods and products (Magnier, 2017). Globally, DMC is equivalent to the material footprint as it considers the system boundaries at the global level (United Nations, 2020b). Unfortunately, at the country level, DMC does not capture the indirect resources needed for the production of goods and products (Calatayud et al., 2016). The DMC $\left(DMC(t)\right)$ equation is defined as follows:

  $$DMC(t) = M(t) + I_{mn}(t) + \sum_{p=1}^{2} I_p(t) - E_{mn}(t) - \sum_{p=1}^{2} E_p(t) \tag{5}$$

  where $M(t)$ is the mining rate of raw phosphorus, $I_{mn}(t)$ is the rate of imports of phosphorus at the mining stage, $I_p(t)$ is the rate of imports for $p = 1, 2$ (fertilizers and feed additives), $E_{mn}(t)$ is the rate of exports at the mining stage, and $E_p(t)$ is the rate of exports for $p = 1, 2$ (fertilizers and feed additives).

- Proportion of phosphorus from secondary production: It indicates the percentage of usable recovered phosphorus in the supply chain (Cobo et al., 2018). Higher percentages indicate higher efficiency of circular P systems (Eq. 3).

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- Amount of material escaping the system: It indicates the material outflow from the system at all stages (European Commission, 2018b). The less material is lost and landfilled the higher the efficiency in material value conservation and the more efficient circular P systems. Mathematical formula showing material escaping the system ($P_o(t)$) is thus the summation of material lost and landfilled across the supply chain of phosphorus:

$$P_o(t) = \sum_{m=1}^{3} PL_m(t) + \sum_{w=1}^{3} PW_w(t) \tag{6}$$

  where $PL_m(t)$ is the amount of material lost from stage $m = 1, 2, 3$ (mining, production and recycling); and $PW_w(t)$ is the mass flow of waste material into landfilling and disposal from waste sector $w = 1, 2, 3$ (manure, wastewater, and solid wastes).

SLCA consists of impact categories and sub-categories of social dimension. Impact categories represent the relevant stakeholders of phosphorus life cycle including workers, local communities, and the society (Table 1). On the other hand, sub-categories represent the causal relationships within the impact category. The process starts by selecting stakeholders and impact categories, followed by the characterization of social indicators, before finally linking them to the system dynamics model of the phosphorus supply chain. Golroudbary et al. (2020, 2019a), El Wali et al. (2019), Chen and Graedel (2016), Scholz and Wellmer (2015), and Scholz et al. (2014) provide quantitative assessments of the phosphorus supply chain. They were mainly used to develop the model of phosphorus supply chain and obtain data inputs. At the country level, material flow data were obtained and compiled from the USGS (2017, 2016, 2015, 2014, 2019, 2018), FAOSTAT (2020d, 2020c), and the United Nations (2020). The detailed input structure, data calculations and data sources can be found in Annex (Tables A.1 and A.2). The selection of social indicators goes in parallel with the list of SDGs. Social indicators are linked to the following stages: mining, production, and recycling. The mining phase covers the extraction as well as the refining and beneficiating processes, production phase covers agricultural production of crops and livestock, while recycling represents wastewater recycling.

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Table 1. Definition of social sustainability indicators in phosphorus supply chain.

Stakeholder categories	Impact category indicators	Definition

Workers	Work safety	Reflects the health status of directly employed workers
	Employment equality	Reflects the employment contribution towards gender equality (male/female)
	Livelihood of workers	Quantifies the number of employees living under poverty
Local communities	Nutrition supply	Refers to the availability of nutrients for the society, higher values or values above the threshold show that the nutrition system is good
	Water use	Measures the amount of water withdrawn for agricultural production
	Employment rate	Measures the employment contribution to the local communities at the national level
	Child labor	Measures the child population involved in economic activities
Society	P efficiency	Refers to the balance of P between inputs as fertilizers and outputs as harvested and cultivated crops
	P security	Reflects the domestic availability of P without dependence on imports.

Each indicator within our assessment exercise is assigned to a target value (Table 2). This allows us to assess the progress of the social impact of phosphorus supply chain.

Table 2. The target values of the social sustainable development indicators.

Social indicator	Unit	Target
Work safety	Accident cases per 100,000 workers	Zero
Employment equality	Ratio of female-to-male employment rate (Dmnl)	1
Livelihood of employees	Employees under the poverty line as percentage of total employees	Zero
Child labor	Children working as percentage of child population	Zero
Employment rate	Employees as percentage of labor force	≥33*
Water use	$m^3\ cpt^{-1}\ yr^{-1}$	≤ 200
Nutrition supply	kg P $cpt^{-1}\ yr^{-1}$	≥ 0.9
P efficiency	kg P $ha^{-1}\ yr^{-1}$	Zero
P security	Domestic P as percentage of available P	100

*The target varies regionally for each country separately. Details on the selection of the target values can be found in the Annex, A section 1 and Table B.3.

Indicators for the workers category correspond to the work safety level, gender equality in employment, and livelihoods of employees (Mancini et al., 2018).

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- Promoting safe and secure working environments corresponds to one of the targets of the eighth SDG goal "Decent work and economic growth". It is measured by the incidence of occupational accidents. The indicator includes the number of fatal ($Ac_{f_m}(t)$) and non-fatal ($Ac_{nf_m}(t)$) accidents per employees engaged, which is reflected in the calculation of the number of accidents.

$$Ac(t) = \frac{\sum_{m=1}^{3}(Ac_{f_m}(t) + Ac_{nf_m}(t))}{\sum_{m=1}^{3} Ep_m(t) \times P_m(t)} \tag{7}$$

where $Ep_m(t)$ is the employment required for the production of 1 tonne of phosphorus at supply chain stage m; and $P_m(t)$ is the mass flow of phosphorus at supply chain stage $m = 1, 2, 3$ (mining, production, and recycling).

- Ensuring women's full and effective participation and equal opportunities in the economic life is one of the targets of the 5th goal in the SDG "Gender equality". This indicator is measured by the employment rates for both genders separately (male and female) at the workplace. Hence, the ratio of female to male employment rate $\left(GE(t)\right)$ is calculated using the following equation:

$$GE(t) = \frac{\sum_{m=1}^{3} F_m(t) * \left(Lf(t)\right)^{-1}}{\sum_{m=1}^{3} M_m(t) * \left(Lm(t)\right)^{-1}} \tag{8}$$

where $F_m(t)$ is the number of female employees engaged in the production at stage m of the supply chain, $m = 1, 2, 3$ (mining, production, and recycling); $M_m(t)$ is the number of male employees engaged in the production at stage m; $Lf(t)$ and $Lm(t)$ are the female and male labor force at time t respectively.

- Eradicating extreme poverty for everyone is the 1st target of the first goal within the SDG framework "No poverty". This study considers employees under the poverty line. We measure the livelihoods of employees through the daily earnings from work. This indicator is reflected by calculating the percentage of employees engaged in the supply chain of phosphorus living under the poverty line $\left(Pov(t)\right)$ through the following equation:

$$Pov(t) = \frac{\sum_{m=1}^{3} \mu_m(t)}{\sum_{m=1}^{3} Ep_m(t) \times P_m(t)} \times 100 \tag{9}$$

where $\mu_m(t)$ is the number of workers at supply chain stage $m = 1, 2, 3$ (mining, production, and recycling), with daily earnings below the threshold; and $Ep_m(t)$ is the number of workers required for the production of 1 tonne of phosphorus at stage m; and $P_m(t)$ is the amount of phosphorus flow at stage m.

Indicators defined to measure the social impact on local communities correspond to nutrition supply (O'Neill et al., 2018), water use and consumption, employment rate and child labor (Mancini et al., 2018).

- Ensuring public access to nutrition and ending all forms of malnutrition are equally important targets for the second goal of the SDG "Zero hunger". This study measures the nutrition supply of the phosphorus chain in line with this goal. Nutrition supply is reflected by the availability of phosphorus for human consumption from both animal-based and crops-based sources. The nutrition supply $\left(NS(t)\right)$ measured in this study corresponds to the availability of phosphorus for human consumption. Thus, the mathematical formula is as follows:

$$NS(t) = \frac{P_a(t) + P_b(t)}{Pop(t)} \tag{10}$$

  $P_a(t)$ and $P_b(t)$ are the annual food production of crops and livestock at time t, respectively; and $Pop(t)$ is the annual population variable.

- Ensuring the sustainable supply and use of fresh water by the year 2030 is the fourth target under the sixth goal in SDG "Ensure access to water and sanitation for all". In our analysis, water use corresponds to water withdrawal for the agricultural production. Hence, the equation for water withdrawal for agriculture $\left(W(t)\right)$ is as follows:

$$W(t) = \frac{\sum_{x=1}^{20} Cr_x(t) \times W_{Cr_x}}{Pop(t)} \tag{11}$$

  where $Cr_x(t)$ is the production rate of crop type $x = 1,2,\ldots,20$; and W_{Cr_x} is water requirement per one tonne of crop type x produced.

- The importance of employment was highlighted in the 5th and the 6th targets of the eighth SDG goal "Decent work and economic growth". This study considers the number of employees involved in individual phosphorus supply chain stages, divided by the labor force per the geographic scale under study. The mathematical formula is as follows:

$$Em(t) = \frac{\sum_{m=1}^{3} Ep_m(t) \times P_m(t)}{Lb(t)} \times 100 \tag{12}$$

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where $Ep_m(t)$ is the number of employees required to produce one tonne of phosphorus at supply chain stage m at time t; and $P_m(t)$ is the mass flow of phosphorus at supply chain stage m at time t; and $Lb(t)$ is the labor force seeking employment.

- Eradicating child labor in all its forms is the 7th target of the 8th goal in the SDG "Decent work and economic growth". This indicator is reflected through the determination of percentage of child population engaged in the supply chain of phosphorus $\left(Cl(t)\right)$. The mathematical formula is as follows:

$$Cl(t) = \frac{cl(t) \times \left(Cr(t) + F_d(t)\right)}{Ch(t) \times Pop(t)} \times 100 \tag{13}$$

where $cl(t)$ is the number of children working to produce one tonne of P in the agricultural sector for crops and livestock; $Cr(t)$ and $F_d(t)$ are the annual production of crops and livestock, respectively; and $Ch(t)$ is the ratio of children population to the total population $\left(Pop(t)\right)$.

Finally, the supply chain indicators for the society category correspond to the nutrition security and nutrients supply independency (Teah and Onuki, 2017). By extension, this means the evaluation of P efficiency and P security (El Wali et al., 2019).

- Achieving the efficient use of natural resources is labelled as the second target of the twelfth goal on the SDG list "Responsible consumption and production". P input into farmlands originates from sources including produced inorganic fertilizers, recycled organic fertilizers and material deposition. P outputs correspond to crop production and cultivation. Hence, the mathematical formula is as follows:

$$P_{ef}(t) = \frac{R(t) + P_f(t) + P_d(t) - GC_R(t) - Cr(t)}{FL(t)} \tag{14}$$

Where $P_{ef}(t)$ is the P balance; $R(t)$ is the amount of materials originating from circular P sources; $P_f(t)$is the amount of fertilizers originating from linear P sources; and $P_d(t)$ is the annual amount of atmospheric deposition of phosphorus; $GC_R(t)$ is the amount of phosphorus from grass cut processes; and $FL(t)$ is the area of farmland available.

- Ensuring access to nutrition for all people is the first target of the second SDG "no hunger". P security is defined as the reliance level on domestic availability of phosphorus. It is measured by the trade as well as

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domestic production activities. This study adopts the European Commission approach in calculating the reliance rate on net imports and annual domestic production (Devauze, 2017).

$$Ps(t) = \frac{\partial(t)}{\left(\sum_{m=1}^{2} \Delta I_m(t)\right) + \partial(t)} \times 100 \tag{15}$$

where $Ps(t)$ is the reliance ratio on imports, $\Delta I_m(t)$ is the net imports at supply chain stage $m = 1, 2$ (mining and production) and $\partial(t)$ is the domestic production rate of phosphate fertilizers.

3. Results and discussion

In this study, the proposed model is used to evaluate the scenarios of phosphorus flow and its social impact on associated stakeholders on the basis of sustainable development goals. The linear economy scenario corresponds to the current P flows from linear sources to the material disposal. The circular economy scenario reflects P flows from circular sources (manure, wastewater and solid waste). The maximum improvement in recycling reaches 45%. This percentage assures the technological feasibility range of phosphorus recycling (El Wali et al., 2018; Scholz and Wellmer, 2018). Also, population growth rate, consumption patterns, farmland and labor force were considered in the design of future scenarios until 2050. Detailed data on growth rate, data distribution, and data sources are presented in Annex (Table A.2).

3.1. Global phosphorus distribution

The results of the dynamic model show a large gap between material availability from the linear sources and that from the circular sources. In 2010 there were around 32 million tonnes and 17 million tonnes respectively of P available from global primary and secondary sources (Figures 3a and 3c). Primary phosphorus available in the non-mining countries represents imports from foreign sources. The results show that there would not be any significant change in the future distribution of available phosphorus from linear and circular sources up to the year 2050, as far as the source reliance is concerned. In the global market linear sources of phosphorus continue to dominate over the circular ones. Global availability of primary phosphorus is estimated to reach around 40 million tonnes P by the year 2050 (Figure 3b). East Asia is the market leader with around 24% of global primary phosphorus, while China's market share is 17%. Northern Africa and Western Asia are estimated to reach a total of around 13 million tonnes P from linear sources, while each one of these regions covers 15 to 17% of global primary phosphorus. Circular

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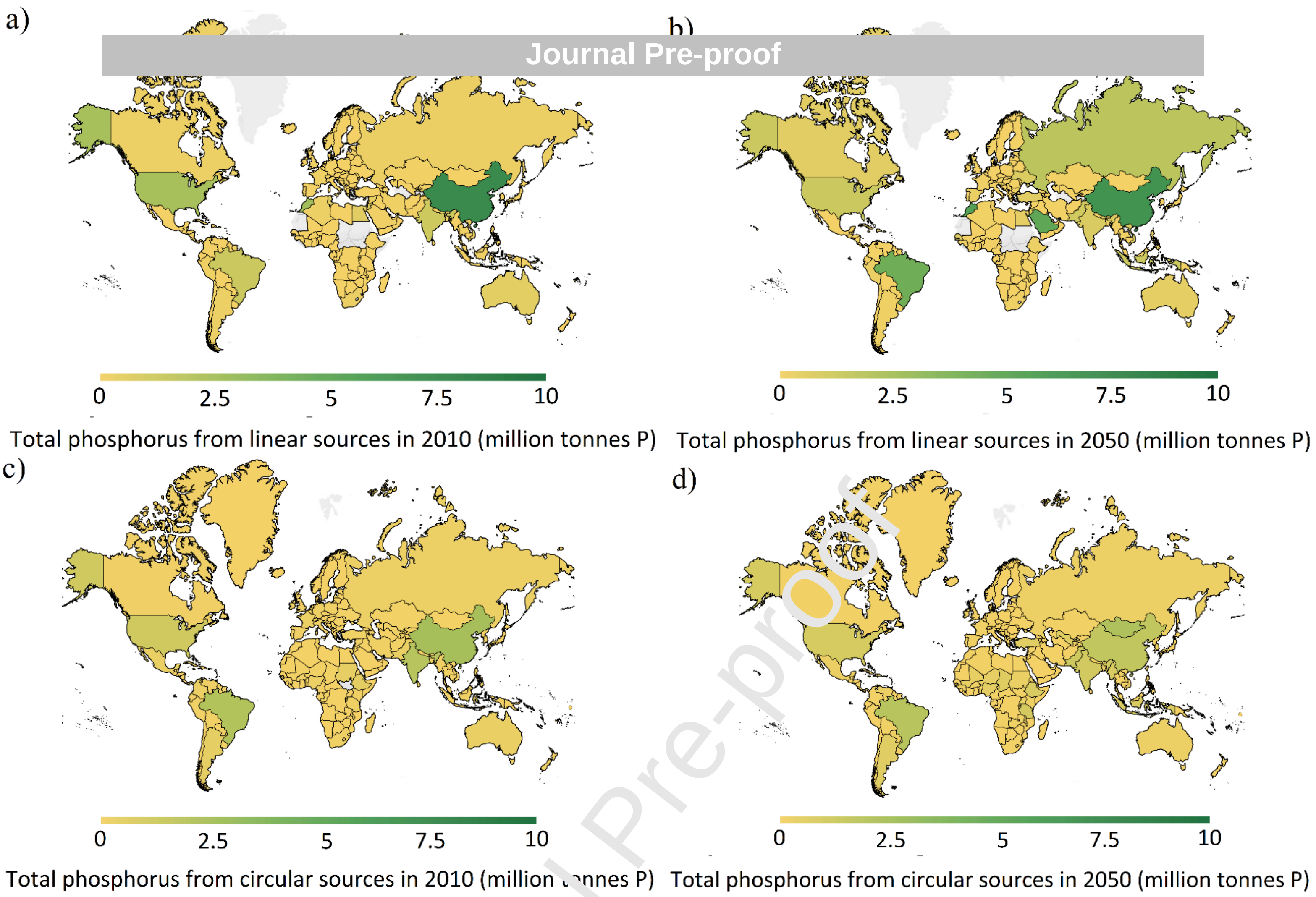

Figure 3. Global phosphorus availability from linear and circular sources (in million tonnes P). Data range is from 0 to 10 million tonnes P. Linear sources include the mined raw phosphorus and imports of mined and chemical fertilizers. Circular sources include recycled phosphorus from wastewater, manure, and solid waste.

sources are estimated to provide up to [illegible]2 million tonnes of phosphorus, from which 22% comes from Eastern Asia, followed by 13% from Central Asia, 12% and 7.3% from Southern America and Europe, respectively (Figure 3d).

The gap in phosphorus mass between the linear and circular sources reflects two issues in the P supply chain: inefficiency in phosphorus flow across supply chain stages and waste generated instead of recovery and recycling (Chen and Graedel, 2016). Table 3 presents the flows of phosphorus across the loss and production channels. It shows that around 23% of global P was either lost or landfilled in 2010 and in 2050 the share will reach 49%. The percentage of fertilizers originating from circular sources reaches an average of 36% within 2010-2050 period. This indicates that over the same period an average of 64% of available phosphorus comes from the linear economic system.

Table 3. Phosphorus flows along the supply chain (millions of tonnes of P).

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Year	**Domestic material consumption**	**Material escaping the system**	**Fertilizers from recycling**	**Proportions of secondary phosphorus (%)**
2010	33.51	8.65	17.08	34.17
2015	34.59	12.16	21.84	37.77
2020	35.16	15.26	21.42	39.14
2025	35.49	17.29	22.25	39.07
2030	36.24	18.22	21.64	39.31
2035	37.92	18.11	21.65	36.21
2040	37.06	18.15	21.64	40.13
2045	38.73	18.93	21.89	37.75
2050	39.89	18.74	21.51	36.87

3.2. Global social development goals of the phosphorus supply chain

Results obtained for the social indicators on the global scale are shown in Figure 4 (a & b). The indicator assumes values between 0 (minimum) and 1 (threshold). The threshold value corresponds to the target value for each indicator. The mathematical formulation of the normalization process is found in Annex A, section 2. The results show the different impact of linear and circular P models on social sustainability of the phosphorus supply chain between 2010 and 2050. Next, we will discuss each indicator separately.

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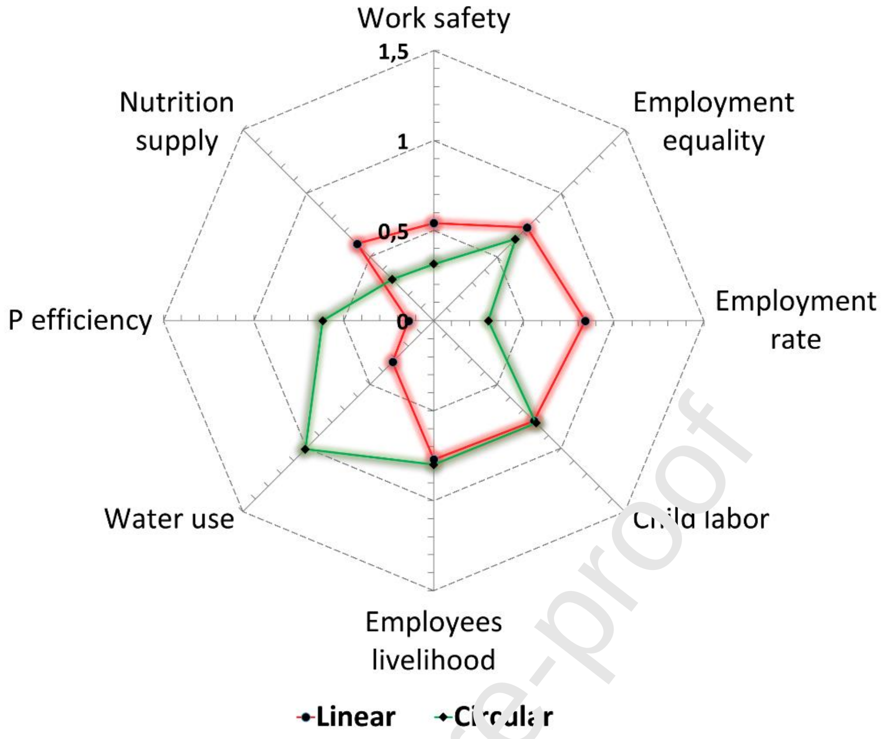
a)



b)

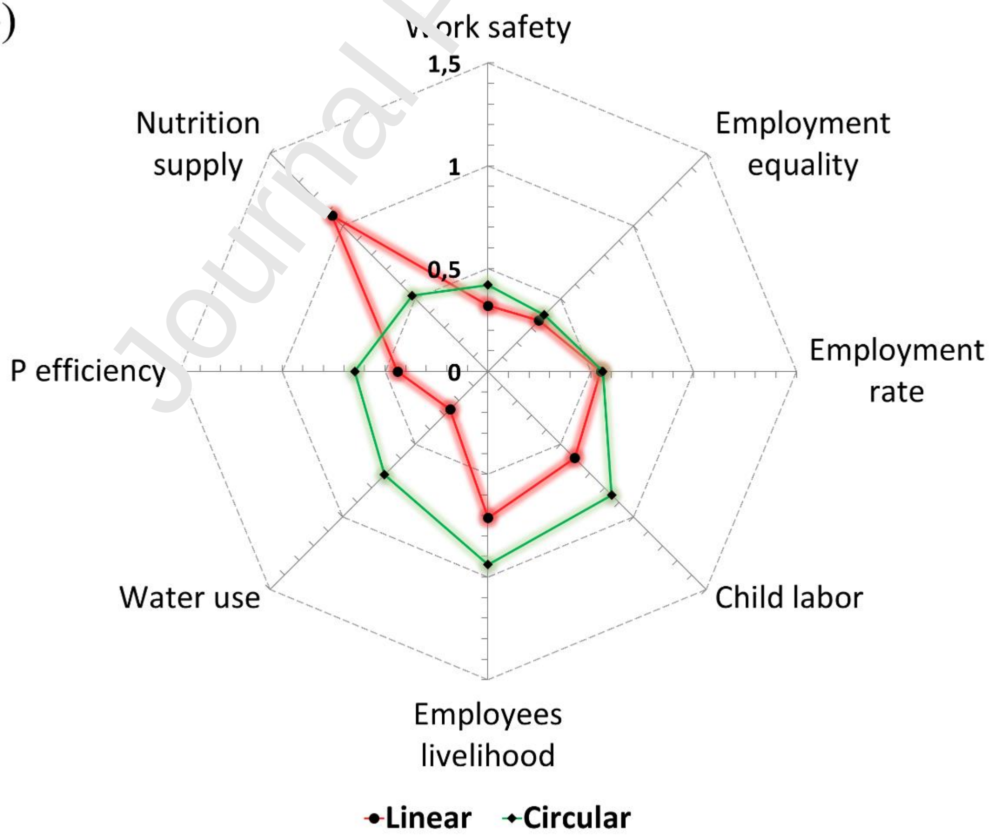


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Figure 4. Comparison of social indicators scores for global supply chain of phosphorus. (a) 2010 and (b) 2050.

- *Work safety*

The work safety indicator includes the incidence rate of accidents occurring at work per worker. Higher score informs about a better occupational health and safety environment with fewer occupational accidents per worker, and vice versa.

The score obtained for the work safety for primary and secondary phosphorus production in 2010 was on average respectively 46% and 69% below the threshold. In both types of production, the supply chain of phosphorus fails to meet the social threshold for this indicator. However, a better working environment for workers is offered in the linear economy model, with a global occupational accident rate of around 183 cases/100,000 workers in 2010 and estimated 272 cases/100,000 workers in 2050, compared to as many as 274 cases/100,000 workers in 2010 and estimated 231 cases/100,000 workers in 2050 in the circular economy. Higher occupational accident rate (around 500 cases/100,000 workers) has been observed in the phosphorus recycling sector than in the mining sector (around 167 cases/100,000 workers). Also the water treatment sector often faces challenging occupational health and safety problems due to the high exposure to hazardous wastes and chemicals leading to injuries and diseases such as cancer, allergic diseases, and fetal harm (Carducci et al., 2018). The transition to a circular economy implies growing occupational challenges as new problems arise from newly adopted techniques and recovery methodologies (Pääkkönen and Koponen, 2018). While the focus of decision makers is solely directed towards the material and economic improvement, these results indicate lower score for work safety in the circular economy.

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- *Employment equality*

The employment equality indicator measures the female to male employment ratio. Higher scores suggest a more equal participation of female and male workers in employment. We consider ‘1’ as the desired threshold of the female-to-male employment ratio. Any score below 1 means that male employment rate is higher than female employment rate in the phosphorus supply chain.

The score obtained for circular production model in 2010 is 0.64 out of 1, revealing a female employment rate by 36% lower than the male employment rate. On the other hand, in the linear economy model the score for female employment rate is around 27% lower than male employment. Our results reveal a score-decreasing trend for both linear and circular production models, which indicates a growing gap in the female-to-male employment ratio. In 2050, the score for circular economy model reaches 0.38, while for the linear economy 0.35 out of 1.

Within the agricultural sector, both production models contribute equally to the ratios of the genders employment rate. Statistical data for 86 countries from the International Labor Organization (ILO) show a 76% gap between the female and male employment rates in recycling by 2010 (ILOSTAT, 2020c). These statistical results widen up the gap in the employment rates between the two genders in the circular phosphorus model.

- *Employment rate*

Results show that initially linear economy offers better employment rates than the circular economy, with an employment rate of around 28% in 2010, whereas the circular economy contributes to the employment rate up to 10% in the same year. The trend observed for this indicator varies between the different production models. In circular economy, the employment rate increases and reaches up to 18% of the global labor force in 2050. On the other hand, the results suggest a decreasing trend in linear employment by 35%, bringing it down to 18% in 2050 as well.

The transition to phosphorus circular economy can create additional job opportunities as argued by Moreau et al. (Moreau et al., 2017) who have provided evidence that circular economy contributes to increases in employment in Finland, France, the Netherlands, Spain, and Sweden. Mainly, more job opportunities could be created in the recycling sector including the wastewater treatment facilities (Teah and Onuki, 2017).

- *Livelihood of employees*

Global efforts aimed to reduce poverty and improve livelihoods of workers and employees are on the rise. For this indicator, higher scores represent lower poverty percentages, and vice versa.

The results show that around 20% to 23% of workers in the P supply chain lived below the poverty line in 2010. Putting in place the circular economy model in the P supply can contribute to the reduction of poverty rate by 6% in 2050. On the other hand, linear production model causes an increase in poverty rate by 26% in 2050. On average, a transition to circular economy in the phosphorus chain is estimated to reduce the poverty rate amongst workers by almost 50%. The reduction of poverty within the circular phosphorus model is manifested by a consistent growth of salaries and wages in the P recycling sectors, particularly in wastewater treatment and recovery (International Labour Organization, 2016).

- *Child labor*

Child labor is deeply rooted in poverty, income insecurity, social injustice, lack of public services, and lack of political will. In this study, we assume a complete eradication of child labor in the European Union, based on the strong prohibition of work by children under 15 years of age in its legislation (Directive 94/33/EC). Higher scores inform about lower child labor rates, and vice versa.

Globally, the linear and circular economy models of phosphorus production are estimated to have engaged respectively 4.25% and 3.8% of child population in 2010. The situation in the linear economy is estimated to worsen as the child labor ratio grows up to 8.1% of total child population by the year 2050 whereas in the circular economy, the rate continues to decline to 2.9%. It shows that, if implemented, the circular economy goes hand in hand with the poverty rate reduction while in the linear economy poverty rates grow constantly.

- *Water use*

The rates of water use per hectare of farmland along the phosphorus supply chain were analyzed. As shown by estimates, linear economy surpasses the boundaries of water use (around 350 m^3/capita in 2010 and reaches 364 m^3/capita in 2050). The circular economy needs 43% of water for agriculture less than the linear economy in 2010. However, water consumption is estimated to grow as well by 32% in the circular production model to reach 264 m^3/capita in 2050. The growth in water consumption in both models results mainly from the increase in agricultural production which is estimated to grow by 28% between 2010 and 2050. On average, the circular economy contributes to the reduction of water consumption to 232 m^3/capita within the 2010-2050 period, which indicates significant savings in the use of water (around 53%) compared to the linear economy.

- *P efficiency*

The efficiency of phosphorus (mainly as a component of fertilizers) corresponds to the phosphorus balance between the input and output rates in the soil. The desired difference value between the input and output is always zero, which is also the threshold value in our study. However, practically, there are always losses and inefficiencies resulting from natural causes such as soil erosions or P use inefficiencies throughout the fertilizer application

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process. This leads the plant to absorb less P than what was applied. In this analysis, higher scores represent smaller amount of phosphorus balance and vice versa.

Globally, in 2010 phosphorus balance of 1.27 kg P/ha from circular sources represents a higher efficiency compared to linear sources, with a balance of 2.85 kg P/ha. The circular economy of phosphorus offers natural fertilizers that improve the soil structure and tilth, as well as reduce erosions from wind and water. (Roberts and Johnston, 2015). Both linear and circular production models fail to achieve the desired threshold, which is a total elimination of inefficiencies in fertilizer application to the soil. Results estimate a growing trend in linear phosphorus efficiency, reaching a score of 0.14 and 0.43 out of 1 in 2010 and 2050, respectively. This result suggests better P application practices adopted in linear production models. Circular phosphorus efficiency follows a growing trend as well although to a lesser extent with the score of 0.65 out of 1 (1.16 kg P/ha) in 2050.

One of the main advantages of the application of P fertilizers obtained under the linear production model is the supply of nutrients to plants within in a shorter time compared to the circular model. This is why efforts should be made to better apply chemical fertilizers to reduce inefficiencies – e.g. apply them at the right time – rather than eliminate the option totally (Li et al., 2020). However, despite the improvements, the circular economy still offers a better P use efficiency score naturally, and is capable of reducing the phosphorus balance by 46% compared to that from linear sources on a global scale.

- *Nutrition supply*

Phosphorus is an essential nutrient for all forms of life. Its shortage will threaten global food production. Our analysis measures the supply of P nutrients for human consumption on an annual basis. The higher the score, the bigger the amount of kgs of P supply per capita in a year, and vice versa.

Based on the data, estimates for 2010 show that the linear economy supplies higher amounts of P nutrients (annual amount of 0.7 kg P/capita) than the circular economy (annual amount of 0.5 kg P/capita). This is mainly the effect of higher linear availability of phosphorus at a global scale (around 32 million tonnes of P) compared to around 20 million tonnes of P available from the circular sources (Figure 3 a&c). However, neither of the two models reached the social threshold which for 2010 was 0.9 kg P/capita annually. Both the linear and circular economy present a growing trend for nutrition supply amounts globally, reaching up to 0.94 kg P/capita for linear

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production and 0.62 kg P/capita for circular production in 2050. The available primary phosphorus is estimated to reach 40 million tonnes and the secondary phosphorus to reach 27 million tonnes in 2050 (Figure 3 b&d).

On average, a complete transition to a global phosphorus circular economy will not ensure meeting the demand of many regions for nutrient consumption. The results indicate a deficit of around 0.38 kg P/capita in 2050. This should also be highlighted in the context of the continuous growth of global population, which is estimated to reach up to 9.73 billion people in 2050.

3.3. Regional social development goals of the phosphorus supply chain

In this section, we discuss the regional analysis of the social development results in phosphorus management, given the two circular and linear economy models (Table 4). The regional data correspond to the average data of countries geographically belonging to a given region. Region compilation follows the UN classification of world countries. Country level data can be found in Annex, Table B.1 (social sustainable development data). The list of regions as well as countries included in them can be found in Annex, Table B.4. Regional results reveal different ways in which circular economy contributes to the tackling of social development issues involved in the phosphorus supply chain. Figure 5 shows the contribution of the circular economy in achieving the social development goals.

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Table 4. Average results of the social development indicators for different regions in the period 2010-2050, in circular economy (CE) and linear economy (LE). A&N: Australia/New Zealand; Ca: the Caribbean; C&S-Am: Central and Southern America; C-As: Central Asia; E-Af: Eastern Africa; E-As: Eastern Asia; E-Eur: Eastern Europe; M-AF: Middle Africa; N-Af: Northern Africa; N-Eur: Northern Europe; Oc: Oceania (excluding Australia and New Zealand); S-Eur: Southern Europe; W-Af: Western Africa; W-As: Western Asia; W-Eur: Western Europe

Region	**Work safety (cases/100,000 workers)**		**Employment equality (Dmnl)**		**Employment rate (%)**		**Poverty rate (%)**		**Child labor (%)**		**Water use (m^3/cpt)**		**Nutrition supply (kgP/cpt)**		**P efficiency (kgP/ha)**		**P security (%)**	
	CE	*LE*	*CE*	*LE*	*CE*	*LE*	*CE*	*LE*	*CE*	*LE*	*CE*	*LE*	*CE*	*LE*	*CE*	*LE*	*CE*	*LE*
E-Af	--	--	0.76	0.75	44	47	29	46	21	19	169	102	0.31	0.32	1.81	1.14	71.4	5.00
M-Af	--	--	0.74	0.74	15	26	21	27	17	10	244	375	0.37	0.39	0.43	0.69	83.8	11.1
W-Af	--	--	0.64	0.60	12.5	12	26	45	21	23	275	173	0.44	0.71	1.41	0.99	90.4	7.9
N-Af	--	--	0.92	0.87	16.2	17	5.6	7.9	31	26	111	443	0.27	1.48	0.74	0.43	37.9	71
W-As	34	483	0.47	0.43	11.2	9.4	1.4	1.2	15	22	126	258	0.32	0.85	1.99	1.58	67.8	28.9
C-As	2.3	5.06	0.88	0.85	17	18	8.2	15	18	32	179	156	0.40	0.47	1.85	1.79	70	37.7
E-As	80	49	0.59	0.58	17	17	2.9	7.1	9.5	19	146	155	0.47	0.59	4.41	4.04	61.5	23.3
Ca	--	--	0.33	0.32	3.7	3	0.24	0.4	16	10	140	71	0.31	0.21	3.41	2.48	74.9	4.9
C&S-Am	559	899	0.36	0.35	5.8	8	2.6	4.9	12.5	25	356	273	0.88	0.96	1.58	1.76	62.2	13.7
N-Am	--	--	0.23	0.24	0.96	1.9	0	0	--	--	314	536	0.94	1.42	0.78	1.32	68.7	61.1
A&N	439	1024	0.28	0.28	3.12	4.4	0	0	0	0	715	792	2.48	2.53	1.49	2.69	53.2	46.1
Oc	--	--	0.40	0.41	14	22	7.12	12	--	--	186	73	0.37	0.43	2.37	0.46	78.7	5.00
E-Eur	122	252	0.52	0.49	29	21	0.02	0.02	0	0	122	309	0.77	0.81	0.91	2.88	43.9	20.9
N-Eur	331	426	0.69	0.69	9	5	0	0	0	0	448	424	1.31	1.15	4.79	3.05	43.8	22.2
S-Eur	417	756	0.58	0.56	13	9	0.01	0.02	2	4	151	156	0.51	0.39	1.51	2.13	60.6	27.9
W-Eur	940	1001	0.54	0.52	2.4	1.5	0	0	0	0	236	198	0.82	0.38	5.91	3.20	55.3	17.9

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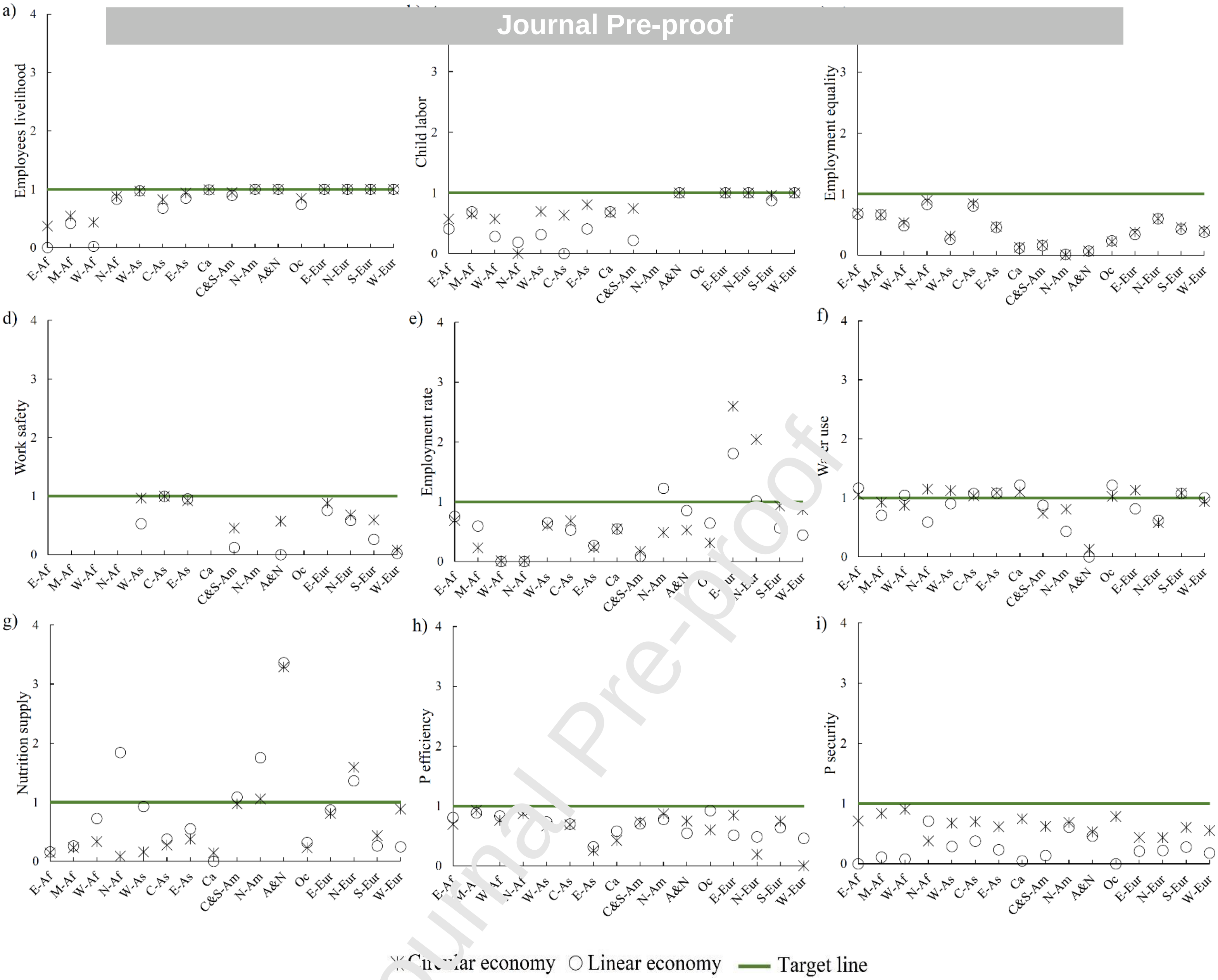

Figure 5. Social sustainable development goals for world regions for a circular and linear economy model of phosphorus supply chain.

Work Safety

The transition to the circular economy is expected to help regions to have a safer working environment in phosphorus supply chain by decreasing occupational accident rates in, e.g., Western Asia by 93% over a period 2010-2050, followed by New Zealand, Central Asia, and Europe where the improvement ranges between 44 and 61%. These results are mainly due to newly adopted initiatives in waste recycling sectors, such as job up-skilling, combating social dumping, ensuring quality jobs and decent pay conditions, as well as having publicly owned and democratically controlled waste services. The goal is to ensure a high level of health and safety for workers as

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proposed by the European Commission (EPSU, 2017). At the opposite end of the spectrum, Eastern Asia – including China – is estimated to face an increase of 58% in occupational accidents in line with the phosphorus circular economy. China is the leading supplier of mined phosphates. The shift to a circular economy in Eastern Asia will eventually shift the occupational accident rates from the mining sector where an average is 49 cases/100,000 workers, to the recycling sector with an average of 80 cases/100,000 workers.

- *Employment equality*

Results indicate improvements in gender equality within the phosphorus supply chain in the top mining countries achieved by implementing the circular economy model in 2010-2050: in Israel by 46%, in Algeria by 34%, in Kazakhstan by 28% and in China by 12%. The male employment rate within the mining sector in those countries exceeds the female employment rate on average by 82% within the analyzed period. The demand for female workforce is concentrated in office and administrative jobs, as well as in professional, service, and sales positions (Fernandez-Stark et al., 2019).

Results show limited variations of gender employment ratios based on regional analysis, where gender equality for this ratio decreases by no more than 5% in Europe, Africa, Australia/New Zealand, the Americas, and Asia. However, no region is estimated to achieve a complete gender equality within its phosphorus supply chain by introducing the circular economy model.

- *Employment rate*

Circular phosphorus economy significantly contributes to the growing employment rate in the region of Northern Europe by 79% in the year 2050, followed by the rest of Europe with the ratio reaching 40-60%. For the Caribbean and Western Asia employment rates are supposed to grow to 23% and 19%, respectively. In Western Africa a slight growth in employment rate by 4% is anticipated (Table 4).

However, a transition to a circular economy can possibly negatively impact the employment trend in local communities, simply because the skills demanded by the new jobs are not totally met by the workforce (ILO, 2019). In addition, phosphorus recycling is rapidly evolving, in particular when it comes to the technical part of it. Hence, recycling techniques are not always accessible (Schipper, 2019). Therefore, Middle Africa, Central and Southern America, Central Asia, Oceania, and Australia/New Zealand are estimated to face a decreasing trend in their

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employment rates in 2010-2050 in the phosphorus circular economy compared to the linear one — 44% for Middle Africa, 37% for Oceania, 29% for Australia/New Zealand, 27% for Central and Southern America, and 6% for Central Asia. Northern and Eastern Africa have the least shrinkage rates by only around 5% within the same period.

Nevertheless, the impact of the transition to circular phosphorus economy on employment rate is visible in the short term. Detailed analysis shows that some top phosphorus mining countries, such as Senegal, Egypt, Morocco, Russia, Tunisia, Israel, Jordan, and Saudi Arabia are estimated to face more than 85% decrease in their employment rate. Other countries in the same situation are Australia, Algeria, Brazil, Peru, Togo, Syria, Canada, and the United States where employment rates will drop between 40 and 80%. The employment rate in Finland, and Mexico will grow by 31% and 68%, respectively.

- *Employees livelihood*

Circular economy may help to decrease poverty of employees engaged in phosphorus supply chain in nearly all regions of the world within the period of 2010-2050. Regional estimates show that East Asia accounts for the highest decrease in poverty (on average by 58%) followed by The Caribbean (by 38%).

The factors defining the poverty status of a country might go well beyond the linear and circular economies. Political instability plays a major role in disrupting economic growth and increasing poverty (Bérenger and Bresson, 2013). Western Asia is estimated to face a 20% increase in poverty within its phosphorus circular economy in the period 2010-2050. This goes in line with an estimated growth in circular employment rates as well.

- *Child labor*

Child labor is used in the mining sector, where tens of thousands of children are engaged in raw resources mining globally. Among the phosphorus mining countries, South Africa, Morocco, and Syria are estimated to face a growth in child labor by up to 80% within 2010-2050 in linear economy. They are followed by Brazil, Peru, and Vietnam with an increase in the same period by 73%, 57% and 29%, respectively.

Theoretically, transition to a circular economy promises an end of the child labor challenge through eradicating poverty (Geissdoerfer et al., 2017). Central and Southern America is expected to achieve reductions in child labor by up to 52% by the year 2050, followed by East and South Asia with 50%, Central Asia up to 38%, Western Asia up to 29% and Western Africa up to 10% (Table 4). Although child labor is often linked primarily to poverty, multiple

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factors play a significant role in shaping child labor rates in a region. Those factors are based on aspects pertaining to culture, geography, and demography (Krauss, 2017). Other regions are against the global sustainable trend by transition into a phosphorus circular economy. Middle Africa and The Caribbean are expected to face child labor growth in the range of 65-68% within the period of 2010 to 2050. The same can be observed for Northern Africa where child labor rate will increase by around 20% and Eastern Africa with 8%.

Regional results suggest that a transition to a circular economy model may lead to a serious problem of reinforcing the child labor challenge for The Caribbean and for the African continent except for its western regions. Therefore, the legal commitment to child labor elimination and extending the social protection of children continue to be sidestepped although the SDG 8.7 target of the UN calls for an end to child labor in all its forms by 2025.

- *Water use*

The transition to circular economy for regions such as North Africa means having a 74% reduction in water use in the phosphorus supply chain in 2010-2050, followed by Eastern Europe, Western Asia, Middle Africa and North America with reductions of 40-60%, and Australia/New Zealand (by 10%). Technically, organic P fertilizers contribute positively to the soil structure and water holding capacity. This leads to less water required for the plant growth (Adugna, 2016). On the other side, regions including the eastern and the western parts of Africa would face an increase in water use by around 64% and 59%, respectively in 2010 and 2050. This issue is followed by the Caribbean, Central and Southern America with a 30% increase and Central Asia with around 14% increase.

The phosphorus chain is estimated to achieve the water use targets by implementing the circular economy in Eastern Africa, Northern Africa, Western Asia, Central Asia, Eastern Asia, Eastern Europe and Southern Europe. However, the rest of the regions violate the water use boundaries despite water savings reported for some regions.

- *P efficiency*

The circular economy contributes to increases in P efficiency by a range of 40-45% in Australia, New Zealand, and North America within a 2010-2050 period. The same has been observed for Middle Africa with a 29% decrease in the P balance. Europe, Central and Southern America are estimated to improve their P efficiency by a transition to the circular economy, with a slight decrease in the P balance around 11%. On the other hand, results show that P efficiency may decrease by the transition to circular economy in regions such as east, west and north of

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Africa as well as in western and central parts of Asia. As for Africa, there is a growth in P balance by an average of 80% in the eastern regions, 71% in the northern region and 41% in the western region of the continent in 2010-2050, followed by Western Asia with an increase of 26% compared to a slight increase of 3% in the part of Central Asia.

The improvement in P efficiency in several regions is not enough to accomplish the target of zero phosphorus balance, while Middle Africa achieves the lowest balance of 0.46 kg/ha within the 2010-2050 period.

- *Nutrition supply*

The transition to circular phosphorus economy will result in decreased nutrition supplies by 81% for North Africa, 62% for Western Asia, 37% for Western Africa, 33% for North America, 20% for Eastern Asia, and 15% for Central Asia as well as Oceania. For other regions, this transition triggers growth of nutrition supplies by 84% for Western Europe, 46% for The Caribbean, 30% for Southern Europe, and 13% for Northern Europe in the 2010-2050 period. The rest of regions maintain the existing levels of nutrition supply with some variation rangingbetween 1 and 3% in the same period.

- *Phosphorus supply security at national scale*

Phosphorus supply security demonstrates the degree of societal reliance on the foreign exporters. Thus, the indicator can only be assessed and analyzed for individual countries. Figure 5 shows the reliance on exporters of phosphorus from different countries in the linear and circular economy models.

The results show that the circular economy improves the security of P supplies in most regions (Figure 6 c&d) compared to linear economy in the 2010-2050 period (Figure 6 a&b). Western Africa is estimated to achieve the highest reduction in phosphorus reliance on imports by up to 89% within the period 2010-2050. Other regions for which phosphorus reliance on imports has decreased include Middle Africa, Eastern Africa, and Oceania. Significant improvement of the security of P supplies within those regions achieved by a transition to the circular economy reflects the lack of domestic production of phosphorus. Quite the opposite, the circular economy fails to improve the security of P supplies in Northern Africa where reliance on imports is estimated to increase by 53%. This means that many countries in this region rely on the linear sources of phosphorus available from the phosphate rock reserves.

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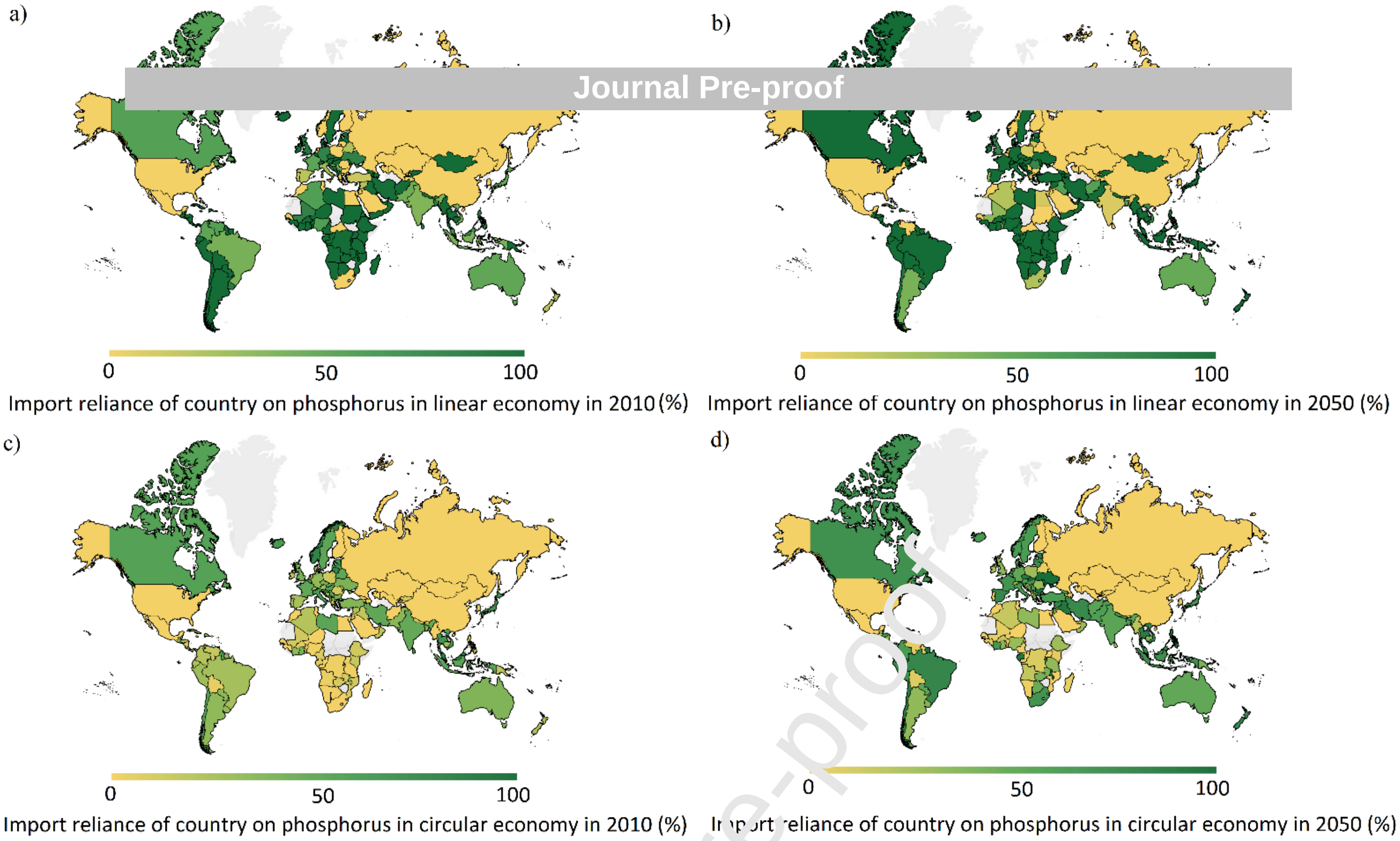

Figure 6. Phosphorus reliance on exporters from different countries (in percentage). (a) linear economy 2010. (b) linear economy 2050. (c) circular economy 2010. (d) circular economy 2050.

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Conclusion

This study focuses on issues related to social sustainability of circular phosphorus economy at regional and global scale by 2050. It aims to address SDG 1 (end poverty in all its forms everywhere), SDG 2 (zero hunger), SDG 3 (ensure healthy lives and promote well-being for all at all ages), SDG 5 (achieve gender equality and empower all women and girls), SDG 8 (promote inclusive and sustainable economic growth, employment and decent work for all) and SDG 12 (ensure sustainable consumption and production patterns) in global phosphorus management.

The results show that the circular economy affects phosphorus flows by different patterns of behavior for each region including balancing and reinforcing social issues in long-term perspective until 2050. Detailed analysis shows that the circular economy contributes to global improvement in the P security for all regions, except Northern Africa where linear economy model offers higher security. The circular production model contributes to reductions in poverty in middle and low-income regions. It also helps the phosphorus chain to achieve employment targets set for

Eastern and Northern Europe. The circular economy model for phosphorus aims to sustain water with a 53% savings worldwide. It maintains the sufficient supply of nutrients in Northern America, Australia/New Zealand, and Northern Europe, while it threatens a decrease in nutrition supply for several regions.

In contrast to the generally optimistic views on the benefits that the circular economy can bring to societies, this paper presents a different perspective by highlighting the paradoxical social effects of phosphorus circularity for different regions in the context of sustainable development goals.

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CRediT authorship contribution statement

Mohammad El Wali: Conceptualization, Methodology, Data curation, Software, Validation, Formal analysis, Writing–Original draft preparation. **Saeed Rahimpour Golroudbary:** Conceptualization, Methodology, Formal analysis, Writing–Editing. **Andrzej Kraslawski:** Conceptualization, Supervision, Writing–Reviewing and Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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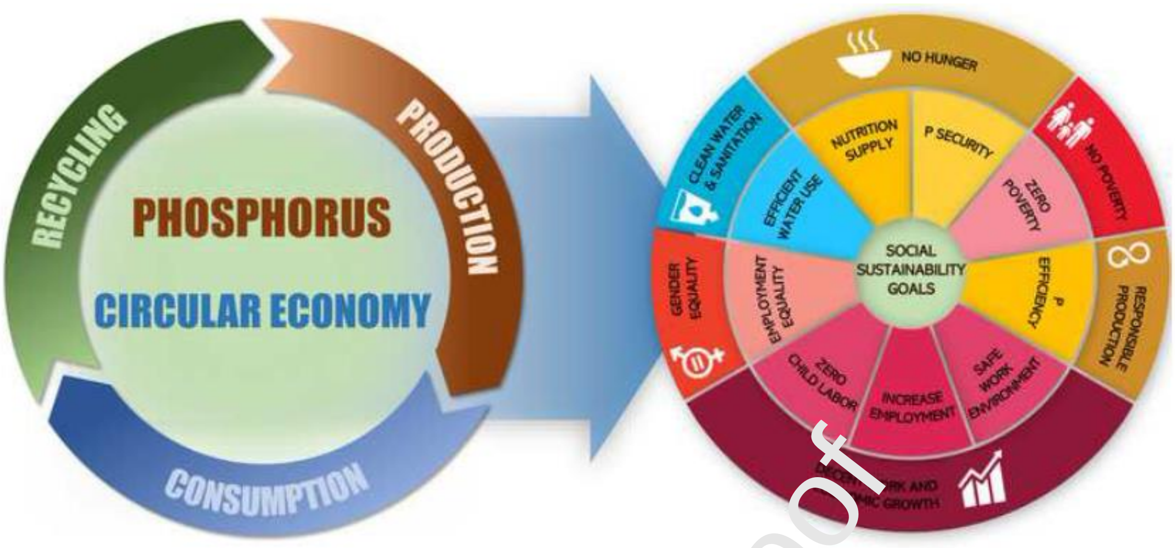

Graphical abstract

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HIGHLIGHTS

- Building model of phosphorus flow to assess social sustainable development goals
- Assessment of effect of linear and circular flows on P supply chain by 2050
- Estimation of social impact of P circularity at regional and global scale by 2050
- Identification of paradoxical impact of phosphorus flows on social sustainability

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