Cite as: Yakovleva, N., Chiwona, A.G., Manning, D.A.C., and Heidrich, O. (In Press). Circular economy and six approaches to improve potassium life cycle for global crop production. Resources Policy, 102426.

Circular economy and six approaches to improve potassium life cycle for global crop production

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ABSTRACT

The United Nations Sustainable Development Agenda 2030 calls for a transformative action to eradicate hunger and poverty and is particularly important for food production in developing countries (see SDG 1 Zero Hunger). Farmers in developing countries apply less potassium fertiliser than those in developed countries due to the high cost of imports and unavailability of domestic supplies. A circular economy approach can improve the efficient use of potassium resources throughout their life cycle from “mine to mouth” by identifying problem areas and assisting in designing supply strategies that help address the needs of farmers. As a nutrient, potassium conventionally follows a linear life cycle from mining. Using secondary data sources and literature, we analyse global demand and supply of potassium to quantify and illustrate the major supply shortages in the Global South.

This study identifies six options to improve potassium availability: (1) expanding conventional potassium mining and distribution systems serves those who can afford globally-traded fertiliser products; (2) seeking alternative sources of potassium, such as remineralisers, that provide a local source that is accessible to poorer farmers, and in many cases helps the circular

economy of local mining operations that focus on other products; (3) improving markets by supporting trade and mitigating some of the disadvantages encountered in developing countries, such as transport and small scale of purchasing; (4) increasing the use of organic fertilisers, such as sewage and manures; (5) reusing crop residues and other farm wastes as sources of potassium, regarding a farm unit as a closed system as far as is practicable; and (6) recycling food waste so that nutrients return to the land, rather than to discard. Existing restrictions and practices mean that there is no single solution to enhance food production in the Global South using the circular economy principles. However, if these circular economy principles and policies are considered at farm to country scale progress can be made.

KEYWORDS: Fertiliser; Potassium; Circular economy; Food system; Global South

1. Introduction

Potassium (K) and phosphorus (P) are minerals produced through conventional mining and are key components of agricultural fertilisers that form essential inputs for plant growth and global food production. In the context of global population growth, fertiliser use is projected to rise due to surging demand for food and arable land (Weinzettel et al., 2013; Wu et al., 2018), biofuels and agricultural produce (Dmitrieva et al., 2017). Attention to date has focused on phosphorus (Cordell et al., 2009), with less paid to potassium availability. A lack of potassium supply is particularly concerning for the Global South (Sheldrick and Lingard, 2004), where domestic potassium production and effective potassium recovery from farming and food waste are largely absent (Ciceri et al., 2015). Lack of potassium poses significant social and economic challenges for poor small-holder farming communities in developing countries of the Global South that seek to improve soil quality, food production, farming yields and incomes, health,

and nutrition in line with the United Nations Sustainable Development Goals (UN SDGs) (FAO, 2016; UN, 2016).

Besides the research on market mechanisms and searches for indigenous sources of mined potassium, there are gaps in academic research examining potential solutions to the supply of potassium in the Global South (Manning, 2010; FAO, 2016). There is a scarce understanding of how developing countries can advance fertiliser production and leapfrog from inefficient production patterns to a sustainable economy, achieving green growth and resources melioration (FAO, 2019; Vazquez-Brust and Sarkis, 2012). Here, the circular economy (CE) can offer valuable mechanisms and principles by revisiting the produce-use-dispose stages of production (Blomsma and Brennan, 2017; Luthra et al., 2019; Upadhyay et al., 2021a) to replace wasteful production methods of conventional industrialised production patterns. The circular economy is capable of advancing economic prosperity and the achievement of the UN SDGs by promoting systems thinking within production and consumption cycles, improving linkages between industrial sectors, reducing waste, and improving resource efficiency. Often studies examine fertiliser flows within a bounded agri-food system (Kelly, 2006; Carraresi et al., 2018). Though some studies establish a connection between food and mineral production when discussing mineral-based fertilisers, they seldom address the needs and contexts of the developing nations (Manning and Theodoro, 2020; Villalba et al., 2008; Wellington and Mason, 2014).

Thus, this paper aims to examine solutions to improve the supply of potassium, especially in developing countries. The paper has specific objectives to: a) define the potassium life cycle as an integrated system of food and mineral production; b) identify solutions to improving potassium fertiliser supply using CE principles and life cycle assessment in production, application, and recovery of potassium (Blomsma and Brennan, 2017; Braungart et al., 2007; Gaustad et al., 2018; Korhonen et al., 2018); and c) discuss barriers for circular economy

implementation in developing countries, making policy recommendations for overcoming these limitations.

In order to respond to the special issue call on “Resources Melioration and Circular Economy” (Luthra et al., 2019), the analysis presented in the paper seeks to understand: a) the connections between mineral resource production and food production in the context of potassium fertilisers; b) the extent to which CE principles can close loops in the potassium life cycle; and c) barriers and drivers for reforming potassium supply in the Global South and building a sustainable potassium life cycle. The novelty of this study lies in detailing the extent of potassium shortages in the Global South, designing an extended view of the potassium life cycle from mineral production to farming, identifying possible solutions to overcoming potassium fertiliser shortages in developing countries and discussing enablers, and challenges for CE adoption in the context of potassium.

The paper is structured as follows. First, the paper reviews how the literature on CE relates to mineral production and potassium supply for food production. After outlining the adopted research methods, the paper examines potassium demand and supply conditions and presents the analysis of six approaches for improving supply using CE principles. Finally, the paper discusses the challenges to CE implementation in developing countries and provides policy recommendations.

2. Literature Review: Circular Economy and Potassium Supply

This section reviews how circular economy principles can be applied in mineral production and specifically in the production and supply of potassium, traded as the commodity ‘potash’.

2.1. Circular economy and mined minerals

Circular economy (CE) is an economic system that offers an alternative to the current unsustainable production system that follows a linear production-use-disposal model by closing the loop with reuse and recycling of waste for further effective production and use (Geissdoerfer et al., 2017; Korhonen et al., 2018; Upadhyay et al., 2021a,b). CE is based on several principles such as resource efficiency, reuse and recycling of materials (Ellen MacArthur Foundation, 2013; 2019; Murray et al., 2017; RSA, 2013). It offers an arsenal of solutions to closing the loop of the production cycle through resource recycling, reuse, remanufacturing, refurbishment, repair, upgrading and associated use of low-carbon energy flows of solar, wind, and biomass (Bridgens et al., 2018; Korhonen et al., 2018; McDonough and Braungart, 2002).

Currently, CE is seen as an umbrella concept that embraces various related concepts. These include life cycle assessment, industrial ecology, industrial symbiosis, closed-loop production, waste management, reverse logistics, waste to energy, reduce-reuse-recycle, industrial parks, cradle-to-cradle, sustainable product design, resource efficiency, and optimisation, and extended producer responsibility (Braungart et al., 2007; Blomsma and Brennan, 2017; Winans et al., 2017). Though CE principles have entered policies and operations of public, private, and non-governmental organisations, it is not certain how CE concepts are contributing to improving production models in developing countries (Ellen McArthur Foundation, 2019; EU, 2014; EU, 2015; Lieder and Rashid, 2016).

With regards to mined minerals, Breure et al. (2018, p. 1127) argue that “*the aim of the circular economy is to reduce the demand for fresh mineral resources, thereby reducing the negative impacts from mining and waste disposal on biodiversity and the quality of the human habitat.*” CE principles can be applied to the production of metals and minerals in several ways. Firstly, reduction in the use of metals and minerals can be achieved through changes in product design, increased efficiency in the use of metals and minerals, and the recycling and reuse of metals and minerals from industrial, construction, and urban wastes (EU, 2018). For instance, nation-

states develop regulations on waste to capture metals at the end-of-life of electric and electronic equipment, construction, and other urban and industrial wastes for further effective use (Rhee, 2016; EU, 2018; UNEP, 2018). Secondly, CE principles can be used by mining and metallurgical enterprises to exchange resources (e.g., water, heat, energy, and waste) with other enterprises through industrial symbiosis initiatives to improve resource efficiency (Dong et al., 2013; Winans et al., 2017). Thirdly, all materials produced in mining, including the by-products, can be marketed, sold, and utilised in order to maximise income and minimise waste and energy (Kinnunen and Kasonen, 2019).

However, the policy imperatives for metal recycling and reuse do not necessarily lead to the end of virgin non-renewable resource extraction. Powered by the growing economic development globally and coupled with sequestration of materials before they enter waste streams again, the demand for extraction of metals and minerals from the Earth's crust is steady (Meinert et al., 2016; Ali et al., 2017; Tanginthai et al., 2019). Production and use of future technologies (such as renewable and low-carbon energy technologies, e-transport, and electronic and electrical equipment) are associated with the consumption of metals and minerals such as rare earth minerals (Manning et al., 2019). This raises concerns about the reliance of future development on mineral extraction and warns of environmental and social dangers associated with extraction processes such as resource depletion, environmental pollution, impact on biodiversity, and both social and community impacts (Bridge et al., 2018; Sanchez-Lopez, 2019). Further, Upadhyay et al. (2021a, 2021b) identify various barriers to the implementation of circular economy such as institutional (e.g., regulation) and market factors (e.g., demand and supply), organisational and cultural barriers, and financial, economic, and technological barriers.

2.2. Potassium fertilisers in developing countries

Potassium (K) is a key component of commercial agricultural fertilisers that improve soil quality and crop yields along with other irreplaceable nutrients necessary for plant growth, nitrogen and phosphorus (Al Rawashdeh and Maxwell, 2014; Ciceri et al., 2015; IPI, 2016; USGS, 2016; Heidrich et al., 2018). Humans and animals require potassium intake as part of their diets to maintain health; it is essential for maintenance of body fluid volume, acid and electrolyte balance, and normal cell function¹ (WHO, 2012). Potassium is naturally found in soils and is applied in agriculture with organic fertilisers (such as crop residues, compost, and manure) and inorganic fertilisers (potassium fertilisers made from mined potash and other geological materials) (PDA, 2008; 2016).

Currently, as much as 90% of mined potassium, derived from geological salt deposits, is used for fertiliser production. The rest is used in industrial water treatment, animal feed supplements, cement, fire extinguishers, and textile production (BGS, 2011; Al Rawashdeh and Maxwell, 2014). In agriculture, the use of mined potassium fertiliser increased since the onset of industrial agricultural systems in the 1950s-1960s and discoveries of mineral potassium deposits in Germany and Canada (Al Rawashdeh and Maxwell, 2014; Ciceri et al., 2015; Al Rawashdeh et al., 2016).

In the light of sustainable developmental priorities expressed by the UN SDGs such as SDG2 Zero Hunger, SDG8 Decent Work and Economic Growth, and SDG12 Responsible Consumption and Production (UN, 2016); efficiency of food production, especially in developing countries, needs to be improved. Effective farming can help improve the livelihood of poor, small-holder farming communities in the Global South, eradicate hunger and improve health and nutrition. To achieve these SDGs, it is essential to advance the agricultural systems

¹ Normally ingested potassium leaves the human body through urine (WHO, 2012).

in developing countries, and particularly increase the availability of affordable potassium fertilisers for farmers in the Global South (Manning, 2010; Martey et al., 2019).

However, there is a dramatic lack of domestic potassium production in the Global South as the majority of potassium is currently mined in the Northern hemisphere (Canada, Belarus, Europe, and Russia) (Ciceri et al., 2015). Grantham (2012) urges that the world community cannot avoid addressing the future regional shortages of mined fertilisers - phosphorus and potassium. If we take a global view, the reserves of potash are not immediately scarce (USGS, 2016) and available reserves will last for the next 400 years at the current consumption rate (Jasinski, 2011). However, future demand for potassium fertilisers will come predominantly from countries in the Southern hemisphere and is linked to expected population growth in Asia, Africa, and South America. The solutions to regional shortages of potassium fertilisers are not well studied and require further investigation (Sheldrick and Lingard, 2004).

3. Research Methods

The paper aims to identify the current and projected demand and supply challenges in the regions, maps the shortages in developing regions, and identify approaches to overcome supply challenges using the CE principles, especially the life cycle assessment view (see Figure 4). In order to achieve these aims, the study: a) reviews the existing trends in potash production and consumption worldwide and identifies the extent of potash deficiency in developing countries of the Global South using secondary data and visualisation of these trends using maps; and then b) identifies six approaches to improving the supply of potassium fertilisers in developing countries by examining the potassium lifecycle and application of CE principles in order to close the loop.

The study adopts an overall positivist approach, with realist ontology and objectivist epistemology (Bryman and Bell, 2015). Whilst the analysis of quantitative secondary data is based on geostatistical and spatial analysis (see Achilleos, 2011; Setianto and Triandini, 2013); the analysis of textual secondary data and literature uses a deductive approach (Irwin, 2013; Borrego et al., 2009). Conceptually, the study applies the principles of circular economy and life cycle assessment to the study of potassium supply (Blomsma and Brennan, 2017; Braungart et al., 2007; Gaustad et al., 2018). The study utilises secondary data on a) production and consumption of potash, reserves, and resources (e.g., USGS, 2019; Sheldrick, 2001); b) demand for fertilisers (e.g., FAO, 2019); and c) population distribution (e.g., UN, 2018). Following Wellington and Mason (2014), this research determines whether the current level of global production, reserves, and resources can meet the future demand for potassium fertiliser by geographical regions.

For the development of maps using ArcGIS 10.6 software, the paper uses data on the production and consumption of potash worldwide reported by Sheldrick (2001), Sheldrick et al. (2002), and Sheldrick and Lingard (2004) who constructed soil nutrient balances at national, regional and global scales. The methodology for calculating nutrient balances, reported by Sheldrick and Lingard (2004), involves detailed calculations of nutrient losses (e.g., leaching, erosion, and gaseous) and gains (atmospheric deposition and sedimentation) through specialised models such as a universal soil loss equation. These soil nutrient balances were calculated on the basis of published data on crops, fertilizer, manure, and nitrogen from FAO databases (FAOSTAT, 2001; Sheldrick and Lingard, 2004).

Maps were generated using the inverse distance weighting (IDW) interpolation method to produce raster surface maps showing the K nutrient dynamics for different countries as reported by Sheldrick (2001). The IDW method is a geostatistical and spatial analysis technique that works on the premise that spatial points are locationally interdependent and points which are spatially close to each other

are more similar than those far apart (Achilleos, 2011; Setianto and Triandini, 2013). The IDW interpolation was used to define the cell values using a linearly weighted combination of a set of K nutrient sample points over each country's total area. The result from this processing was a raster surface map showing the K nutrient dynamics for the different countries.

In order to identify the approaches to improving potassium supply, we use the process suggested by Gaustad et al. (2018), whereby information is collected from academic literature as well as insights gathered through interaction with the industry, including at the 2nd International Workshop on Alternative Potash in June 2017 (<https://conferences.ncl.ac.uk/alternativepotash-iwap/>). Conceptual and statistical information about flows of potassium along the stages of lifecycle was combined with information from circular economy literature to provide insights about which circular economy principles are the most applicable to overcoming shortages of potassium. A variety of technological and economic opportunities and constraints are reported under each identified approach gathered from academic studies.

Using the review of existing academic studies on potassium production and consumption, we depict the potassium lifecycle from mining of potash to food production and consumption stages and demonstrate the movement of resources through the stages. Through “closing the loop” on the movement of resources and applying the principles of circular economy (Blomsma and Brennan, 2017), we identify and describe potential avenues for improving the supply of potassium for fertiliser production in the Global South. Here, we propose six such approaches to improve the fertiliser supply, application, and recovery in import-dependent countries of the Global South. Finally, the paper discusses the potential challenges and limitations of scaling up these six suggested solutions.

4. Results

4.1. Potassium demand and supply in developing countries

The global demand for fertiliser nutrients (expressed as $N+P_2O_5+K_2O$) is increasing at 2.6% per annum (FAO, 2019) (see Table 1). This trend is associated with increasing consumption of animal protein (Roberts, 2009), fresh fruits and vegetables (Al Rawashdeh et al., 2016; FAO, 2016), and biofuel production (USGS, 2009; Canter et al., 2015), in the context of rising economic affluence and population growth (Weinzettel et al., 2013). The USGS (2019) forecasts that world potash consumption will increase from 42.2 million tonnes in 2018 to 46.2 million tonnes in 2022 with major demand coming from Africa (demand growth at 3.6% per annum), South America (2.9% per annum), and Asia (2.9% per annum) (Heffer and Prud'homme, 2016). With global reserves of potash (K_2O) at 3.7 billion tonnes and new large-scale production of polyhalite², current potassium production rates appear to meet the global demand (USGS, 2016).

Nutrients	2015	2016	2017	2018	2019
Nitrogen (N)	112,539	113,955	115,498	116,905	118,222
Phosphate (P_2O_5)	42,113	42,865	43,785	44,652	45,527
Potash (K_2O)	31,973	32,802	33,629	34,452	35,257
Total	186,625	189,622	192,912	196,009	199,006

Table 1: World demand for fertiliser nutrients ($N+P_2O_5+K_2O$) until 2019, thousand tonnes. Source: FAO, 2019.

Depletion of soil quality and land degradation is a major concern for human development and food security in developing countries. This is linked to agricultural and agronomical challenges, low per capita food production, poverty, slow economic development, and climate change effects (Sanchez, 2002; Gilbert, 2012; Mukuve and Fenner, 2015; Martey et al., 2019). Land degradation and especially potassium deficiency in sub-Saharan Africa (Sheldrick, 2001)

² Polyhalite can be used as multi-nutrient mined fertiliser that contains K in addition to Mg, Ca, and S (Pavuluri et al., 2017).

continues due to overgrazing, soil erosion, and ineffective cropping systems (Mukuve and Fenner, 2015; Wu et al., 2018). Inorganic fertilisers are applied at rates below recommended levels causing serious losses in agricultural productivity (Sheldrick and Lingard, 2004).

Despite being a home to 15% of the global population, Africa accounts for 3% of the world's fertiliser consumption and 1.9% of potash consumption in 2013 (FAO, 2015). Authors argue that increased application of potassium fertilisers and improved fertiliser management can increase production yields, reduce soil degradation and tackle food nutrition challenges in Africa (Bumb and Baanante, 1996; Larson and Frisvold, 1996; Sheldrick and Lingard, 2004). Access to potassium fertilisers in sub-Saharan Africa is low and the continent solely depends on imports (Mukuve and Fenner, 2015; FAO, 2016). Market constraints for African farmers to access fertilisers include high prices, costly transportation, absence of large-scale potash mines, and lack of domestic potassium production (Sanchez, 2002; Sheldrick and Lingard, 2004; Ciceri et al., 2015; Al Rawashdeh et al., 2016; USGS, 2016; Martey et al., 2019).

Figures 1-3 summarise the state of potassium demand and deficiency globally. Considering population growth and distribution (UN, 2018 population data), the demand for increased volumes of food supply will come from Asia, North America, South America, then Europe and Africa in that decreasing order. As South Asia and Europe are more densely populated, these regions would require more fertiliser input per unit area. Figure 1 shows that by 2001 most soils worldwide were depleted in K. This means almost all countries globally need K inputs to replenish their soil K depletion, which can mainly be attributed to soil mining through crop growth. Greater focus needs to be on the more populous regions of Asia. Africa's population has also been increasing at alarming rates and is expected to double from 1.1 billion in 2010 to close to 2 billion in 2040, Therefore more efforts are also needed to increase K fertiliser inputs in African soils.

Figure 1. Annual soil potassium nutrients balance per hectare per year for globally, in tonnes from input, uptake and depletion from all sources. *Source:* Using data from Sheldrick (2001).

Figure 2 shows the total potassium nutrient inputs from all sources per unit area (tonnes/km²) for different countries in 2002. However, as shown in Figure 2, only Europe and China seem to be tackling the K fertiliser scarcity in relation to their population dynamics. Africa, South Asia and North America, and Australia have low K nutrient inputs. Based on the population dynamics and possible fertiliser demand, there is a greater need to increase K fertiliser production and supply in the Global South. Figure 3 shows global K input from commercial fertilisers by tonnage. There is very little K input from commercial fertiliser for Africa, Asia and some parts of North America, and South America. China has higher fertiliser inputs probably due to its economic strength.

Figure 2. Total potassium nutrient inputs from all sources per unit area (tonnes/km²) for different countries in 2002. *Source:* Using data from Sheldrick (2001).

Figure 3. Potassium nutrients from commercial fertilisers input into the soil by farmers per country (in tonnes). *Source:* Using data from Sheldrick (2001).

4.2. Six approaches to improving supply of potassium fertilisers in developing countries

The potassium life cycle incorporates both mineral and food productions and the current system is largely linear (see Figure 4). However, there are opportunities to close the cycle with the application of CE principles and improving resource melioration, which are discussed below.

Figure 4: Potassium life cycle. *Source:* Authors own, adapted from Potash Development Association (2008, 2016). Note: In shade are the dominant stages in the potassium life cycle.

The study identifies six approaches to improve the supply of potassium fertiliser in the Global South. First, improvement of geological information and searching for conventional potash mineral deposits in regions such as Africa, Asia, and South America. The second approach promotes a search for alternative, possibly unconventional, sources of potash in the Global South that would be suitable for soils in tropical and sub-tropical climates. The third approach focuses on improving the information on farm practices and improving the existing channels of trade between potash producing nations and potassium-consuming nations. The fourth approach encourages a reduction in using mineral fertilisers and promotion of organic fertiliser use in large-scale agricultural production. The fifth approach calls for a systemic change and departure from large-scale industrialised production to small-scale, close-cycle production where fertiliser nutrients are produced from organic manures and farm wastes. Lastly, the sixth approach looks at recycling all different types of food and farm waste to produce fertiliser nutrients that contain potassium for use in agricultural production. The enablers and triggers of each approach and the benefits for farmers in the Global South are examined below.

4.2.1. Expand traditional production: search for conventional potash mineral deposits

The traditional approach is to expand conventional potash production and develop mines in the Global South that would form a supply basis for regional potassium fertiliser production. However, almost all potash (this term refers to a number of different mineral salts that contain potassium³) is mined in just 8 countries: Canada, Russia, Belarus, and Israel, followed by smaller producers such as China, Germany, Jordan, and the US. In Europe, Germany, Spain,

³ Potash is mined in various forms: potassium chloride (KCl or muriate of potash), potassium sulphate (K_2SO_4), potassium-magnesium sulphate ($K_2SO_4 \cdot 2MgSO_4$), and potassium nitrate (KNO_3) (Al Rawashdeh and Maxwell, 2014; USGS, 2009). The mineral polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$) is a new multi-nutrient product (14% K_2O ; Kemp et al., 2016), currently mined at one location in the UK (Boulby mine) with a new mine being built near Whitby (Anglo American, 2020). Potassium chloride (KCl) is currently the main K fertiliser product, which contains about 60% of potash (K_2O) equivalent. About 93% of the world's mined potash is used by the fertiliser industry (USGS, 2009).

and the UK are the leading producers of potash (BGS, 2011; Table 2). The US Geological Survey (2019) reports no large potash mines in Africa at the moment, but significant mines are planned for development in Congo (Brazzaville) – Kola Project (Reuters, 2018), Eritrea – Colluli potash project (Forbes, 2019), and Ethiopia. Outside traditional potash-producing countries, new potash mine projects are being planned in Argentina, Australia, Laos, and Peru, and have been considered in Thailand (Hite and Japakasetr, 1979). Cumulatively, all new mines and expansion of old mine projects are expected to increase world potash production capacity to 64.6 million tonnes of K₂O equivalent in 2022, which roughly corresponds to current use plus the deficit reported by Sheldrick et al. (2002).

Geological exploration for commercially viable deposits of potash, including K as a component of natural multi-nutrient fertilisers such as polyhalite, is conducted by private companies. The potassium market is fairly small in terms of the number of actors; not only there are few potassium-producing countries, but few large companies are operating in the market globally. Al Rawashdeh et al. (2016) cite high barriers to entry in the potassium mining industry as it is highly concentrated, which puts limitations to the expansion of the industry. Amongst the largest producers of fertilisers is PotashCorp from Saskatchewan that has recently agreed to merge with a smaller producer, Agrium, to create a crop nutrient group worth \$30bn in market capitalisation (FT, 2016a). Other producers include Mosaic (USA), Uralkali (Russia), Belaruskali (Belarus), Yara (UK), Israel Chemicals (Israel and UK), and K+S (Germany) (PotashCorp, 2014). Following the takeover of Sirius Minerals, Anglo American plc is building the Woodsmith Mine in the UK to produce polyhalite; the new mine plans to have zero waste (Anglo American, 2020). Israel Chemicals already produces polyhalite from the nearby Boulby Mine (FT, 2016b).

Country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015e
Belarus	4,800	4,605	4,970	4,970	2,490	5,250	5,500	4,760	4,240	6,290	6,500
Brazil	405	405	405	471	385	453	454	425	430	311	311
Canada	10,120	8,360	11,100	10,500	4,320	9,788	11,000	8,980	10,100	11,000	11,000
Chile	370	450	500	559	692	800	980	1,050	1,050	1,200	1,200
China	600	600	2,000	2,750	3,000	3,200	3,700	4,100	4,300	4,400	4,200
Germany	3,600	3,620	3,600	3,280	1,800	3,000	3,010	3,120	3,200	3,000	3,000
Israel	2,060	2,200	2,200	2,300	2,100	1,960	1,960	1,900	2,100	1,770	1,800
Jordan	1,230	1,036	1,090	1,220	683	1,200	1,380	1,090	1,090	1,260	1,250
Russia	5,500	5,720	6,600	6,730	3,730	6,260	6,500	5,470	6,100	7,380	7,400
Spain	500	437	580	435	435	415	420	420	420	715	700
UK	600	480	427	427	427	427	427	470	470	610	610
USA	1,200	1,100	1,100	1,100	700	930	1,000	900	960	850	770
Others	65	65	12	11	12	-	-	-	-	50	50
World total	31,100	29,100	34,600	35,000	20,800	33,700	36,400	32,700	34,500	38,800	38,800
Annual growth	n/a	-6.4%	18.9%	1.2%	-40.6%	62.0%	8.0%	-10.2%	5.5%	12.4%	0%

Table 2. Global potassium producing countries, thousand metric tonnes. *Source:* US Geological Survey (2016).

Note: 2015e – estimated output for 2015.

Country	Recoverable ore	K2O equivalent
Belarus	3,300,000	750,000
Brazil	300,000	13,000
Canada	4,200,000	1,000,000
Chile	n/a	150,000
China	n/a	210,000
Germany	n/a	150,000
Israel	n/a	270,000
Jordan	n/a	270,000
Russia	2,800,000	600,000
Spain	n/a	20,000
UK	n/a	70,000
USA	1,500,000	120,000
Others	250,000	90,000
World total	n/a	3,700,000

Table 3: Global reserves of potash, thousand metric tonnes. *Source:* US Geological Survey (2016).

Note: n/a – data not available.

4.2.2. *Find new mineral sources: Search for alternative sources of potash*

Leonardos et al. (2000) and Ciceri et al. (2015) argue that alternative sources of potash need to be sought that are suitable for deeply leached tropical soils in the Global South. Alternative sources of nutrient K from locally occurring rocks and minerals can enable subsistence farmers to use a range of rocks as remineralizers (Van Straaten, 2002; Manning and Theodoro, 2020). Access to these avoids the major capital investment that is required to fund the exploration and development of deep mining of conventional potash. There may be fewer market incentives and less private funding available to develop major potash mines in the Global South for bulk commodities (Ciceri et al., 2015; Al Rawashdeh et al., 2016). Instead, Leonardos et al. (2000) argue that the adoption of large-scale commercial agriculture systems in the Global South, following the paradigm of intensive agriculture borrowed from North America and Europe, brings negative environmental consequences.

Given that the indigenous agricultural systems in the Global South maintained soil quality and food production previously, Leonardos et al. (2000) support propositions for small-scale agriculture that combine the use of inorganic or mineral fertilisers (such as phosphate or silicate rock) with organic sources of nutrients for plant growth. In the context of the Global South, Leonardos et al. (2000) promote an idea of using locally sourced fertilisers to support subsistence and modern agriculture, bearing in mind that the majority of farm units are small (in Brazil, only 10% of farm units produce the commodity crops that Brazil is famous for, and 90% produce crops for domestic consumption (Manning and Theodoro, 2020). In such cases, the ‘stone meal’ can be provided at low cost by local producers and small-scale miners; the use of these materials is now embedded in Brazilian federal law through the regulation of ‘remineralizers’ (Manning and Theodoro, 2020).

Ciceri et al. (2015) and Leonardos et al. (2000) suggest that the search for alternative sources

of potassium should be encouraged, as conventional soluble potassium fertilisers are not entirely appropriate for soils in tropical and sub-tropical zones. In many cases, the use of crushed rock as a remineralizer embeds a circular economy concept; many mines and quarries that produce crushed rock aggregate for the construction industry find that this creates a new market for ‘crusher fines’ that might previously have been regarded as a waste. In addition, Figures 5-7 show K nutrient inputs into the soils using some alternative sources namely manure, human sewage, and crop residues. In each case, China has better strategies for ensuring the use of manure, sewage, and crop residues as alternative potash sources. There is very low utilisation of manure as a K source in Africa, East Asia, and North America. Similarly, the least use of sewage as alternative potash sources is in Africa, East Asia, and the Americas. The use of crop residues as K sources is also least in Africa, East Asia, and some parts of Europe.

Figure 5. Potassium nutrients from manure input into the soil by farmers per country (in tonnes). *Source:* Using data from Sheldrick (2001).

Figure 6. Potassium nutrients from sewage input into the soil by farmers per country (in tonnes). *Source:* Using data from Sheldrick (2001).

Figure 7. Potassium nutrients from crop residues input into the soil by farmers per country (in tonnes). *Source:* Using data from Sheldrick (2001).

The use of remineralizers, as pioneered by Brazil, involves the use of silicate rocks capable of providing a range of elements. Those richest in K include feldspar and especially nepheline-bearing rocks, which have been considered as sources of K for decades. The release of K from these rocks depends on the dissolution rates of their component minerals, as explained by Manning (2010). Although trials have been carried out in Norway (Bakken et al., 2000), silicate rocks are better suited for use in tropical oxisols, where silicate minerals are inherently unstable, with most successful trials being reported from these (Tavares et al., 2018).

4.2.3. Improve markets: support of potassium fertiliser trade in developing countries

In order to increase the availability of potassium fertilisers to farming communities and combat soil degradation, improve soil fertility and assist inefficient local markets, governments in developing countries have introduced fertiliser subsidy programmes, such as in sub-Saharan Africa (Martey et al., 2019). Importing potassium fertilisers, poor availability of information, costly transportation, and distribution all conspire to increase fertiliser prices, and contribute to low fertiliser use and thus poor soil management. On average, African farmers pay between 30-50% more than their counterparts in Europe and North America to purchase K fertiliser (Roberts and Vilakazi, 2014). As a result, there is very little use of commercial fertilisers in Africa and other similar parts of the Global South. Figure 8 shows the percentage of commercial fertiliser input as a proportion of total inputs from all K sources, namely commercial fertilisers (Figure 3), manure (Figure 5), sewage (Figure 6), and crop residues (Figure 7).

Figure 8. Percentage of potassium fertiliser over total input into the soil by farmers per country (in tonnes). *Source:* Using data from Sheldrick (2001).

It is clear in Figure 8 that for most countries in the Global South, less than 9% of total K nutrients input in their soils come from the conventional fertilisers. The average intensity of fertiliser use in sub-Saharan Africa is approximately 8-9 kg/ha, compared with 80 kg/ha globally (Marquis et al., 2013; USAID and IFDC, 2015). The intensity has generally been highest in Southern (16 kg/ha) and Eastern (8 kg/ha) African countries and lowest in the Sudan Sahel (4 kg/ha) and Central Africa (3 kg/ha) (Kelly, 2006). On a household level, Sheahan and Barret (2017) (cited in Martey et al., 2019) report that based on a study of six African countries, inorganic fertiliser use across all households is the highest in Malawi (146 kg/ha), followed by Nigeria (128 kg/ha), Ethiopia (45 kg/ha), Tanzania (16 kg/ha), Niger (2.5 kg/ha), and Uganda (1.2 kg/ha).

While about 65% of Africa's population were engaged in the agricultural sector by 2013, the sector showed low productivity accounting for only 32% of the continent's gross domestic

product (Marquis et al., 2013). This was largely due to inadequate fertiliser utilisation, especially in smallholder farming. The various legislative frameworks operating in different countries also contribute to the operation of the fertiliser markets in Africa. In some African countries barriers to the fertiliser market include restrictions on who is allowed to import and sell fertiliser in certain parts of the countries. Some countries also have restrictive business policies such as tax and non-tariff regimes which deter potential investors from investing and trading in fertiliser supply on national or regional scales (USAID and IFDC, 2015).

There have been many policy changes in most sub-Saharan African countries, including the liberalisation of agricultural input and output markets. One example of these was the Structural Adjustment Programmes, through which governments stopped controlling prices of fertilisers. This enabled the private sector to take control over fertiliser markets (Marquis et al., 2013). Several policies have been implemented following the New Partnership for Africa's Development (NEPAD) of the African Union with the view of promoting fertiliser demand and supply (Marquis et al., 2013). One such initiative was the opening of the region to allow fertiliser supply. For example, Ethiopia opened up for investment in the fertiliser manufacturing industry including granting a mining concession to the Allana Potash company, which sought to produce 1 million tonnes/year of muriate of potash (MOP) at their Danakhil mine. The DRC has also attracted investment for the Sintouka potash project from Australia to develop a mine in the DRC, which was expected to begin production of 1.8 million tonnes/year by 2015 (Marquis et al., 2013), although this has been delayed (USGS, 2019).

Another policy decision that has been made in many African countries is the strengthening of the agro-dealer sector to improve the quality of their service delivery. This was done to increase sales and access to the local farming communities. These initiatives included providing credit guarantees and loans to the upcoming agro-dealers so that they can import and distribute fertilisers more easily. For example, in Kenya, Rwanda, Burundi, Tanzania, and Ghana, a not-

466 for-profit organisation called the One Acre Fund offers loans for fertiliser and seeds to local
467 farmers with a minimal interest repayment, which is used to cover operational costs.

468 In addition, some governments and their development partners have also committed themselves
469 to improve the market linkages for vulnerable communities through the Africa Fertilizer and
470 Agribusiness Partnership (AFAP). Founded in 2011 by the NEPAD, AGRA, IFDC, the African
471 Development Bank (ADB) and the Agricultural Market Development Trust, AFAP's main goal
472 has been to provide targeted support to the fertiliser supply chain. This is an initiative that
473 operates mainly in Ghana, Ethiopia, Tanzania, Kenya, and Mozambique, and enables private
474 sector participation in fertiliser market development by supporting them with finances for
475 fertiliser imports/production, blending, and supply to vulnerable communities such as
476 smallholder farmers, local agro-dealers and fertiliser warehouses.

477 In a related development, other governments established fertiliser subsidies as a vehicle of
478 promoting the purchase of fertiliser at low prices and increasing access to the poor rural farming
479 communities. For example, in Malawi, the Government introduced the targeted farm input
480 fertiliser subsidy programme (FISP) in the early 2000s to help vulnerable farmers. Under this
481 initiative, Government subsidises heavily the prices of fertiliser and seeds so that farmers can
482 purchase the fertiliser and other inputs at lower prices from the agro-dealers. Fertiliser is
483 supplied to rural areas mainly through the state-owned Agriculture and Marketing Cooperation
484 (ADMARC) and the Smallholder Farmers Fertiliser Revolving Fund of Malawi (SFFRM) and
485 other private traders. However, this initiative faces challenges including over-dependency on
486 donor funding (Chirwa and Dorward, 2013) and a long fertiliser supply chain, and uncertainty
487 over its sustainability from the ports to the farmers.

488 In addition, Ott (2012) adds that the farmgate fertiliser price is controlled by various factors
489 including the synergies between demand and supply which are further subject to world

economic factors, such as transport costs, raw materials, and commodity prices, as well as population growth. For example, Malawi's geographic location as a land-locked country greatly contributes to higher fertiliser costs than in neighbouring countries such as Tanzania and Mozambique. Malawi relies on three major seaports, namely Nacala and Beira (Mozambique), Dar es Salaam (Tanzania), and to some extent Durban (South Africa). Marquis et al. (2013) observed that this problem is also faced by other sub-Saharan African countries, thereby increasing the prices of fertilisers to US\$200/tonne higher than free on board (fob) prices on the global markets. Therefore, additional costs apart from the purchasing prices also originate from importation through neighbouring countries' ports. Transport costs from the port to Malawi's capital, Lilongwe, where the fertiliser is delivered, blended, and redistributed countrywide, are US\$50 to >US\$200 per tonne.

4.2.4. Reduce: reduce inorganic fertiliser use by increasing organic fertiliser use in large-scale food production

Technological methods are being developed to recover nutrients from food and farming waste that have potassium content. For instance, in China, where food security is at the top of the national policy agenda, reduction in self-sufficiency in food production, population growth, limited cropland, and growing urbanisation are seen as trends threatening future food security (He et al., 2017). Limitations in the domestic supply of fertiliser inputs to farms in China are recognised with policies to stabilise fertiliser consumption (Bai et al., 2016). Bai et al. (2016) report that the Chinese government initiated a policy of 'Zero Fertiliser Growth by 2020' to reduce the use of inorganic fertilisers in farming. Bai et al. (2016) suggest that potassium can be applied to cropland in a form of manure from animal farming to replace inorganic potassium fertilisers, although these policies are yet to be proved effective.

The major premise of this approach is to link two types of large-scale, industrialised food

productions (animal and crop) by diverting by-products of meat production as inputs into crop production. Potentially, the same can be replicated in the countries of the Global South even at smaller farming scales. Recycling manure and recovery of nutrients for fertiliser production divert production away from mineral-based potassium fertiliser and increases organic fertiliser production. However, this system also has its limitations, as large-scale meat production requires animal feed input and relies on crop production, and harmful residues from veterinary medications may cause problems. Overall, meat production is recognised as the most damaging for the environment, as a major contributor to global carbon emissions, although it does improve soil carbon sequestration.

4.2.5. Reuse: reuse organic and inorganic fertiliser in close-cycle agricultural systems

Currently, there are constrained applications of potassium recycling. Potassium follows a one-way stream from extraction to use in agriculture, consumption, and disposal ultimately via river drainage systems into the ocean. Potassium can be applied to soil not only from mineral-based fertilisers, but also from manure, crop residue, and compost (Sheldrick and Lingard, 2004; PDA, 2008; DEFRA, 2010; Dawson and Hilton, 2011; Elser and Bennett, 2011). To maintain soil quality, methods such as agroforestry can be used (Binam et al., 2014). Studies acknowledge that due to minimal use of commercial fertilisers and increasing agroforestry techniques, small-holder farmers can improve soil quality through the utilization of green manure and compost (Binam et al., 2014).

For organic farming, conventional chemical fertilisers are not used, and nutrient management focuses on nutrient recycling through integrated management of crop and livestock production (Nowak et al., 2015). Importantly, these practices promote local mass flows, exchanging materials from livestock to crop production and designing a holistic approach to farming at a local level to maintain soil quality and enhance food production (PDA, 2008; Nowak et al.,

2015). Organic farming actively uses mined potassium fertilisers, which are acceptable where need can be justified, providing their production avoids chemical processing (Soil Association, 2003; PDA, 2008). There are clear opportunities for promoting integrated farming systems in developing countries and engaging with organic farming principles.

4.2.6. Recycle nutrients: recycle farming and food waste for fertiliser production

Studies on recycling and recovery of nutrients from food waste or the animal food chain suggest promising recovery rates of valuable NPK nutrients and reapplication for food and crop production (Zheng et al., 2020). Advancement of nutrient recycling technologies from farming waste can aid in closing the loop for nutrients and reduce the loss of nutrients (Jurgilevich et al., 2016). However, because of natural losses (given that soil is an open system), inorganic fertilisers cannot be fully replaced with recycled nutrients, but supplement the recovery of nutrient material (see Bai et al., 2016). Elser and Bennett (2011) report that valuable nutrients, potentially usable in agriculture, are lost with food waste; and as much as 40% of food is wasted by households in developed countries (Mirabella et al., 2014). Capturing the nutrients from composting of food waste presents another route for recycling potassium for farming. Recycling food waste in developing countries, especially in populous urban areas, can be added to nutrient recycling that supplies peri-urban farming. Here, technologies around anaerobic digestion and valorisation of food waste with the participation of food retailers could prove useful (Ng et al., 2019).

5. Discussion

Based on the study of potassium supply, we identify three main challenges to the implementation of circular economy principles in developing countries: technological, market,

and institutional factors. Our research adds to the growing body of research on barriers to circular economy implementation (Upadhyay, 2021b).

Firstly, in the context of technology, although advancement of mineral exportation and production, as well as improvement of farm and waste techniques to improve recovery at farm level, are ongoing, there is still room for improving the recycling of nutrients from agriculture and scaling up these technologies for availability to farmers in the Global South. Tilton et al. (2018) suggest that support of new technologies and innovation is the paramount solution to short and long-term shortages of resources, as this solution can enhance efficiencies of primary production and recycling and develop substitutes to existing resources.

Secondly, with regards to the market factors, there are many market challenges within the mineral and food systems that relate to mineral investment and distribution of fertilisers to farmers in developing countries. There is a need for a systematic approach to the development of agriculture in the Global South, including investment to improve infrastructure and availability of credit including the development of market mechanisms to drive affordable trade in fertilisers.

Thirdly, institutional challenges in the Global South relate to the governance of mineral and food production, including legislation, investment regimes, taxation, and sector regulation. Sohn (2006) notes that a favourable institutional environment favours certain mineral production growth. Thus, countries in the Global South could promote investment and development of potassium mining to encourage local potash production for agriculture.

To address the three challenges, the six approaches proposed in our research provide a structure for policy formulation and can be used in combination. These approaches integrate two major paradigms of modern food production, one that relies on industrialised agriculture and depends on large-scale mono food production and the second that promotes small-scale food production

585 and relies on a combination of farm practices and encourages amongst others organic
586 production (Sonnino and Marsden, 2006). These conventional and alternative agri-food systems
587 both have a place in developed countries and thus potassium fertilisers supply should adjust to
588 the evolving food production patterns (Manning and Theodoro, 2020).

589 Applying CE principles to the potassium life cycle demonstrates high levels of food waste in
590 developed countries that require adjustments in the generation and utilization of food and
591 farming waste (Mirabella et al., 2014). Neither the industrialised food system nor the alternative
592 production system can substantially reduce the use of inorganic fertilisers and offer a
593 completely closed cycle without compromising farming cost, soil quality, and food production
594 rates.

595 Industrialised, large-scale, and export-oriented agri-food production is linked to industrialised
596 global mineral supply, dominated by developed country players. This system overlooks the
597 interests of poor, small-holder farmers in the Global South due to differences in production
598 scales, investment, and market power. Government and international organisations could be
599 supporting regional fertiliser supply in developing countries by: a) promoting conventional and
600 alternative potassium discovery and production domestically and supporting agro-geological
601 research; b) encouraging transparency of market information to improve fertiliser markets; c)
602 supporting agri-food research, application of nutrient reuse and recycling and encouraging
603 sustainable farming practices; d) enhancing resource efficiency practices through food and
604 farming waste recycling for nutrient recovery. It is desirable for companies starting potassium
605 extraction projects in the Global South to enter into collaborations with regional partners to
606 address inefficient farming, food insecurity and promote the development of fertiliser markets,
607 effective soil management, and food production.

608 There are limitations to this study. First, it is based on secondary data analysis only, and it lacks

primary qualitative and quantitative data collection on specific circumstances of potassium supply limitations and solutions in individual countries, regions, or mine projects. Further research could examine how potassium mining projects in the Global South can contribute to improving regional food security and assisting small-holder farmers to improve farming yield and incomes using primary data – but at this time there are no such mining projects. Second, the study takes a global, macro view and does not examine what the potassium life cycle would be at a meso level of a region or micro level of an organisation such as a mine, farm, or fertiliser producer with an application to specific types of food production. Further research could investigate collaboration between small-holder farming and small-scale mining leading to potassium fertiliser or remineraliser production. Finally, future studies could compare the management of potassium supply between countries, looking at institutional factors that are conducive to SDG 1 No Poverty and SDG 2 Zero Hunger through efficient fertiliser supply. Further research can examine how to overcome barriers and hindrances to the implementation of circular economy principles in developing countries.

6. Conclusions

We suggest that the answer to improving the use of potassium for optimised yields of agri-food production in the Global South can be found in a hybrid solution that advances both conventional agri-food production and a small-holder alternative system. Agri-food production using conventional food growing and processing technologies and associated large-scale mined potassium production will continue to strengthen food production industries in the Global South. Within this system, the search for new large-scale potassium deposits and investment into their exploitation will increase the potassium supply in the Global South. As an alternative to large-scale conventional food production, a small-holder food production system uses

closed-cycle farming production approaches and, *de facto*, CE principles of reuse, recycle nutrients on farms. This alternative system can be associated with small-scale production of mined potassium using small-scale mining, alternative sources of K, and small-scale processing methods – this solution would require scaling up of technologies that would be affordable to small-holder farmers in the Global South.

Finally, regional cooperation for the development of regional fertiliser production and distribution is essential in regions of potential domestic potash production such as in East Africa to benefit the regional farming communities and aid in the expansion of regional fertiliser markets. If policy makers are guided by circular economy principles, at all scales as suggested in this study, appropriate and effective options that improve potassium nutrient supply for crop production can be considered for different economic and social circumstances.

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