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► To cite this version:

Natalia Yakovleva, Annock Chiwona, David A.C. Manning, Oliver Heidrich. Circular economy and six approaches to improve potassium life cycle for global crop production. *Resources Policy*, 2021, 74, pp.102426. 10.1016/j.resourpol.2021.102426 . hal-04702937

HAL Id: hal-04702937

<https://hal.science/hal-04702937v1>

Submitted on 13 Nov 2024

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

Natalia Yakovleva ^{a*}, Annock G. Chiwona^b, David A.C. Manning^c, Oliver Heidrich^d

* corresponding author

^aNewcastle University London, Newcastle University Business School, Newcastle University, 102 Middlesex Street, London, E1 7EZ, United Kingdom, email: natalia.yakovleva@ncl.ac.uk, tel. +44 (0) 2037522448.

^bSchool of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom, email: a.a.chiwona2@ncl.ac.uk , tel. +44 (0) 191 208 6889.

^cSchool of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom, email: david.manning@ncl.ac.uk, tel. +44 (0) 191 208 6610.

^dSchool of Engineering, Newcastle University, Tyndall Centre for Climate Change, Newcastle upon Tyne, NE1 7RU, United Kingdom, email: oliver.heidrich@ncl.ac.uk, tel. +44 (0) 1912086610.

Declarations of interests: none

25 food production in the Global South using the circular economy principles. However, if these
26 circular economy principles and policies are considered at farm to country scale progress can
27 be made.

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

29

30 **1. Introduction**

31 Potassium (K) and phosphorus (P) are minerals produced through conventional mining and
32 are key components of agricultural fertilisers that form essential inputs for plant growth and
33 global food production. In the context of global population growth, fertiliser use is projected
34 to rise due to surging demand for food and arable land (Weinzettel et al., 2013; Wu et al.,
35 2018), biofuels and agricultural produce (Dmitrieva et al., 2017). Attention to date has
36 focused on phosphorus (Cordell et al., 2009), with less paid to potassium availability. A lack
37 of potassium supply is particularly concerning for the Global South (Sheldrick and Lingard,
38 2004), where domestic potassium production and effective potassium recovery from farming
39 and food waste are largely absent (Ciceri et al., 2015). Lack of potassium poses significant
40 social and economic challenges for poor small-holder farming communities in developing
41 countries of the Global South that seek to improve soil quality, food production, farming
42 yields and incomes, health, and nutrition in line with the United Nations Sustainable
43 Development Goals (UN SDGs) (FAO, 2016; UN, 2016).

44 Besides the research on market mechanisms and searches for indigenous sources of mined
45 potassium, there are gaps in academic research examining potential solutions to the supply of
46 potassium in the Global South (Manning, 2010; FAO, 2016). There is a scarce understanding
47 of how developing countries can advance fertiliser production and leapfrog from inefficient

48 production patterns to a sustainable economy, achieving green growth and resources
49 melioration (FAO, 2019; Vazquez-Brust and Sarkis, 2012). Here, the circular economy (CE)
50 can offer valuable mechanisms and principles by revisiting the produce-use-dispose stages of
51 production (Blomsma and Brennan, 2017; Luthra et al., 2019; Upadhyay et al., 2021a) to
52 replace wasteful production methods of conventional industrialised production patterns. The
53 circular economy is capable of advancing economic prosperity and the achievement of the UN
54 SDGs by promoting systems thinking within production and consumption cycles, improving
55 linkages between industrial sectors, reducing waste, and improving resource efficiency. Often
56 studies examine fertiliser flows within a bounded agri-food system (Kelly, 2006; Carraresi et
57 al., 2018). Though some studies establish a connection between food and mineral production
58 when discussing mineral-based fertilisers, they seldom address the needs and contexts of the
59 developing nations (Manning and Theodoro, 2020; Villalba et al., 2008; Wellington and
60 Mason, 2014).

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

69 In order to respond to the special issue call on “Resources Melioration and Circular
70 Economy” (Luthra et al., 2019), the analysis presented in the paper seeks to understand: a) the
71 connections between mineral resource production and food production in the context of
72 potassium fertilisers; b) the extent to which CE principles can close loops in the potassium

73 life cycle; and c) barriers and drivers for reforming potassium supply in the Global South and
74 building a sustainable potassium life cycle. The novelty of this study lies in detailing the
75 extent of potassium shortages in the Global South, designing an extended view of the
76 potassium life cycle from mineral production to farming, identifying possible solutions to
77 overcoming potassium fertiliser shortages in developing countries and discussing enablers,
78 and challenges for CE adoption in the context of potassium.

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

85

86 **2. Literature Review: Circular Economy and Potassium Supply**

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

89 ***2.1. Circular economy and mined minerals***

90 Circular economy (CE) is an economic system that offers an alternative to the current
91 unsustainable production system that follows a linear production-use-disposal model by
92 closing the loop with reuse and recycling of waste for further effective production and use
93 (Geissdoerfer et al., 2017; Korhonen et al., 2018; Upadhyay et al., 2021a,b). CE is based on
94 several principles such as resource efficiency, reuse and recycling of materials (Ellen

95 MacArthur Foundation, 2013; 2019; Murray et al., 2017; RSA, 2013). It offers an arsenal of
96 solutions to closing the loop of the production cycle through resource recycling, reuse,
97 remanufacturing, refurbishment, repair, upgrading and associated use of low-carbon energy
98 flows of solar, wind, and biomass (Bridgens et al., 2018; Korhonen et al., 2018; McDonough
99 and Braungart, 2002).

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

109 With regards to mined minerals, Breure et al. (2018, p. 1127) argue that “*the aim of the*
110 *circular economy is to reduce the demand for fresh mineral resources, thereby reducing the*
111 *negative impacts from mining and waste disposal on biodiversity and the quality of the human*
112 *habitat.*” CE principles can be applied to the production of metals and minerals in several
113 ways. Firstly, reduction in the use of metals and minerals can be achieved through changes in
114 product design, increased efficiency in the use of metals and minerals, and the recycling and
115 reuse of metals and minerals from industrial, construction, and urban wastes (EU, 2018). For
116 instance, nation-states develop regulations on waste to capture metals at the end-of-life of
117 electric and electronic equipment, construction, and other urban and industrial wastes for
118 further effective use (Rhee, 2016; EU, 2018; UNEP, 2018). Secondly, CE principles can be
119 used by mining and metallurgical enterprises to exchange resources (e.g., water, heat, energy,

120 and waste) with other enterprises through industrial symbiosis initiatives to improve resource
121 efficiency (Dong et al., 2013; Winans et al., 2017). Thirdly, all materials produced in mining,
122 including the by-products, can be marketed, sold, and utilised in order to maximise income
123 and minimise waste and energy (Kinnunen and Kasonen, 2019).

124 However, the policy imperatives for metal recycling and reuse do not necessarily lead to the
125 end of virgin non-renewable resource extraction. Powered by the growing economic
126 development globally and coupled with sequestration of materials before they enter waste
127 streams again, the demand for extraction of metals and minerals from the Earth's crust is
128 steady (Meinert et al., 2016; Ali et al., 2017; Tanginthai et al., 2019). Production and use of
129 future technologies (such as renewable and low-carbon energy technologies, e-transport, and
130 electronic and electrical equipment) are associated with the consumption of metals and
131 minerals such as rare earth minerals (Manning et al., 2019). This raises concerns about the
132 reliance of future development on mineral extraction and warns of environmental and social
133 dangers associated with extraction processes such as resource depletion, environmental
134 pollution, impact on biodiversity, and both social and community impacts (Bridge et al.,
135 2018; Sanchez-Lopez, 2019). Further, Upadhyay et al. (2021a, 2021b) identify various
136 barriers to the implementation of circular economy such as institutional (e.g., regulation) and
137 market factors (e.g., demand and supply), organisational and cultural barriers, and financial,
138 economic, and technological barriers.

139 ***2.2. Potassium fertilisers in developing countries***

140 Potassium (K) is a key component of commercial agricultural fertilisers that improve soil
141 quality and crop yields along with other irreplaceable nutrients necessary for plant growth,
142 nitrogen and phosphorus (Al Rawashdeh and Maxwell, 2014; Ciceri et al., 2015; IPI, 2016;
143 USGS, 2016; Heidrich et al., 2018). Humans and animals require potassium intake as part of

144 their diets to maintain health; it is essential for maintenance of body fluid volume, acid and
145 electrolyte balance, and normal cell function¹ (WHO, 2012). Potassium is naturally found in
146 soils and is applied in agriculture with organic fertilisers (such as crop residues, compost, and
147 manure) and inorganic fertilisers (potassium fertilisers made from mined potash and other
148 geological materials) (PDA, 2008; 2016).

149 Currently, as much as 90% of mined potassium, derived from geological salt deposits, is used
150 for fertiliser production. The rest is used in industrial water treatment, animal feed
151 supplements, cement, fire extinguishers, and textile production (BGS, 2011; Al Rawashdeh
152 and Maxwell, 2014). In agriculture, the use of mined potassium fertiliser increased since the
153 onset of industrial agricultural systems in the 1950s-1960s and discoveries of mineral
154 potassium deposits in Germany and Canada (Al Rawashdeh and Maxwell, 2014; Ciceri et al.,
155 2015; Al Rawashdeh et al., 2016).

156 In the light of sustainable developmental priorities expressed by the UN SDGs such as SDG2
157 Zero Hunger, SDG8 Decent Work and Economic Growth, and SDG12 Responsible
158 Consumption and Production (UN, 2016); efficiency of food production, especially in
159 developing countries, needs to be improved. Effective farming can help improve the
160 livelihood of poor, small-holder farming communities in the Global South, eradicate hunger
161 and improve health and nutrition. To achieve these SDGs, it is essential to advance the
162 agricultural systems in developing countries, and particularly increase the availability of
163 affordable potassium fertilisers for farmers in the Global South (Manning, 2010; Martey et al.,
164 2019).

165 However, there is a dramatic lack of domestic potassium production in the Global South as

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

166 the majority of potassium is currently mined in the Northern hemisphere (Canada, Belarus,
167 Europe, and Russia) (Ciceri et al., 2015). Grantham (2012) urges that the world community
168 cannot avoid addressing the future regional shortages of mined fertilisers - phosphorus and
169 potassium. If we take a global view, the reserves of potash are not immediately scarce (USGS,
170 2016) and available reserves will last for the next 400 years at the current consumption rate
171 (Jasinski, 2011). However, future demand for potassium fertilisers will come predominantly
172 from countries in the Southern hemisphere and is linked to expected population growth in
173 Asia, Africa, and South America. The solutions to regional shortages of potassium fertilisers
174 are not well studied and require further investigation (Sheldrick and Lingard, 2004).

175

176 **3. Research Methods**

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

186 The study adopts an overall positivist approach, with realist ontology and objectivist
187 epistemology (Bryman and Bell, 2015). Whilst the analysis of quantitative secondary data is
188 based on geostatistical and spatial analysis (see Achilleos, 2011; Setianto and Triandini,

189 2013); the analysis of textual secondary data and literature uses a deductive approach (Irwin,
190 2013; Borrego et al., 2009). Conceptually, the study applies the principles of circular
191 economy and life cycle assessment to the study of potassium supply (Blomsma and Brennan,
192 2017; Braungart et al., 2007; Gaustad et al., 2018). The study utilises secondary data on a)
193 production and consumption of potash, reserves, and resources (e.g., USGS, 2019; Sheldrick,
194 2001); b) demand for fertilisers (e.g., FAO, 2019); and c) population distribution (e.g., UN,
195 2018). Following Wellington and Mason (2014), this research determines whether the current
196 level of global production, reserves, and resources can meet the future demand for potassium
197 fertiliser by geographical regions.

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

207 Maps were generated using the inverse distance weighting (IDW) interpolation method to produce
208 raster surface maps showing the K nutrient dynamics for different countries as reported by
209 Sheldrick (2001). The IDW method is a geostatistical and spatial analysis technique that works on
210 the premise that spatial points are locationally interdependent and points which are spatially close
211 to each other are more similar than those far apart (Achilleos, 2011; Setianto and Triandini, 2013).
212 The IDW interpolation was used to define the cell values using a linearly weighted combination
213 of a set of K nutrient sample points over each country's total area. The result from this processing

214 was a raster surface map showing the K nutrient dynamics for the different countries.

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

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

234

235 **4. Results**

236 ***4.1. Potassium demand and supply in developing countries***

237 The global demand for fertiliser nutrients (expressed as N+P₂O₅+K₂O) is increasing at 2.6%
 238 per annum (FAO, 2019) (see Table 1). This trend is associated with increasing consumption
 239 of animal protein (Roberts, 2009), fresh fruits and vegetables (Al Rawashdeh et al., 2016;
 240 FAO, 2016), and biofuel production (USGS, 2009; Canter et al., 2015), in the context of
 241 rising economic affluence and population growth (Weinzettel et al., 2013). The USGS (2019)
 242 forecasts that world potash consumption will increase from 42.2 million tonnes in 2018 to
 243 46.2 million tonnes in 2022 with major demand coming from Africa (demand growth at 3.6%
 244 per annum), South America (2.9% per annum), and Asia (2.9% per annum) (Heffer and
 245 Prud'homme, 2016). With global reserves of potash (K₂O) at 3.7 billion tonnes and new
 246 large-scale production of polyhalite², current potassium production rates appear to meet the
 247 global demand (USGS, 2016).

Nutrients	2015	2016	2017	2018	2019
Nitrogen (N)	112,539	113,955	115,498	116,905	118,222
Phosphate (P ₂ O ₅)	42,113	42,865	43,785	44,652	45,527
Potash (K ₂ O)	31,973	32,802	33,629	34,452	35,257
Total	186,625	189,622	192,912	196,009	199,006

248 **Table 1:** World demand for fertiliser nutrients (N+P₂O₅+K₂O) until 2019, thousand tonnes.
 249 *Source:* FAO, 2019.

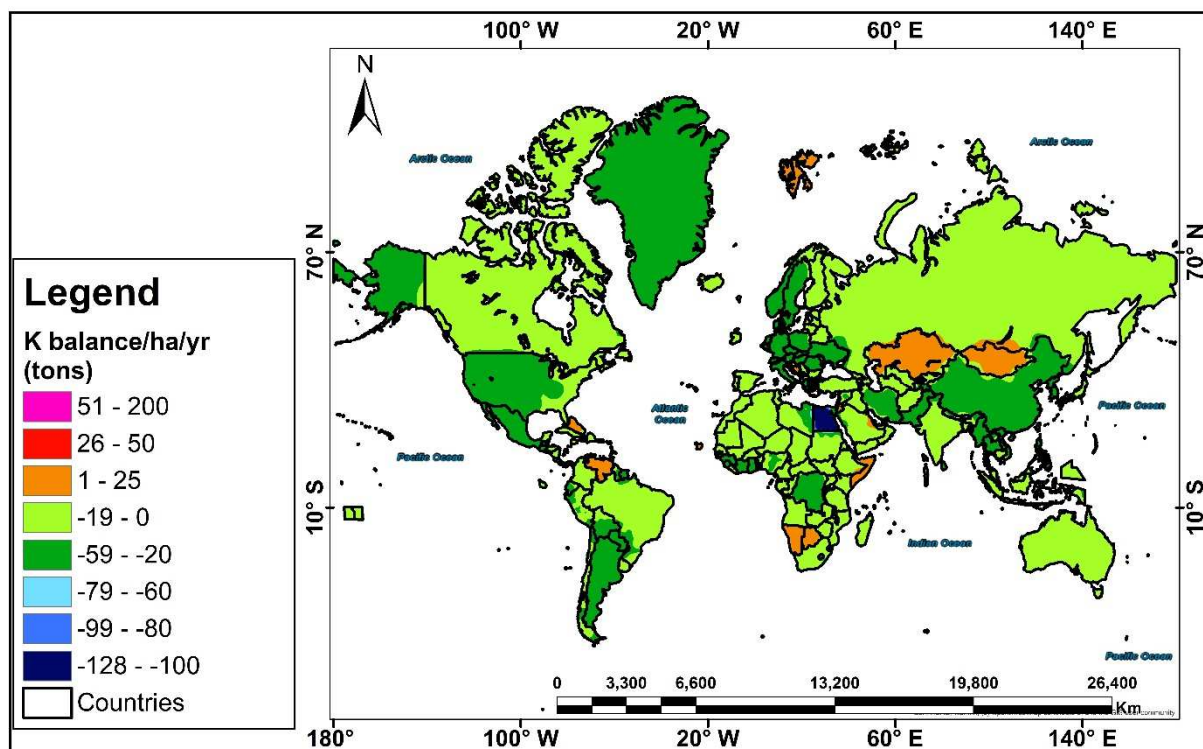
250
 251 Depletion of soil quality and land degradation is a major concern for human development and
 252 food security in developing countries. This is linked to agricultural and agronomical
 253 challenges, low per capita food production, poverty, slow economic development, and climate
 254 change effects (Sanchez, 2002; Gilbert, 2012; Mukuve and Fenner, 2015; Martey et al., 2019).
 255 Land degradation and especially potassium deficiency in sub-Saharan Africa (Sheldrick,
 256 2001) continues due to overgrazing, soil erosion, and ineffective cropping systems (Mukuve
 257 and Fenner, 2015; Wu et al., 2018). Inorganic fertilisers are applied at rates below

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

258 recommended levels causing serious losses in agricultural productivity (Sheldrick and
259 Lingard, 2004).

260 Despite being a home to 15% of the global population, Africa accounts for 3% of the world's
261 fertiliser consumption and 1.9% of potash consumption in 2013 (FAO, 2015). Authors argue
262 that increased application of potassium fertilisers and improved fertiliser management can
263 increase production yields, reduce soil degradation and tackle food nutrition challenges in
264 Africa (Bumb and Baanante, 1996; Larson and Frisvold, 1996; Sheldrick and Lingard, 2004).
265 Access to potassium fertilisers in sub-Saharan Africa is low and the continent solely depends
266 on imports (Mukuve and Fenner, 2015; FAO, 2016). Market constraints for African farmers
267 to access fertilisers include high prices, costly transportation, absence of large-scale potash
268 mines, and lack of domestic potassium production (Sanchez, 2002; Sheldrick and Lingard,
269 2004; Ciceri et al., 2015; Al Rawashdeh et al., 2016; USGS, 2016; Martey et al., 2019).

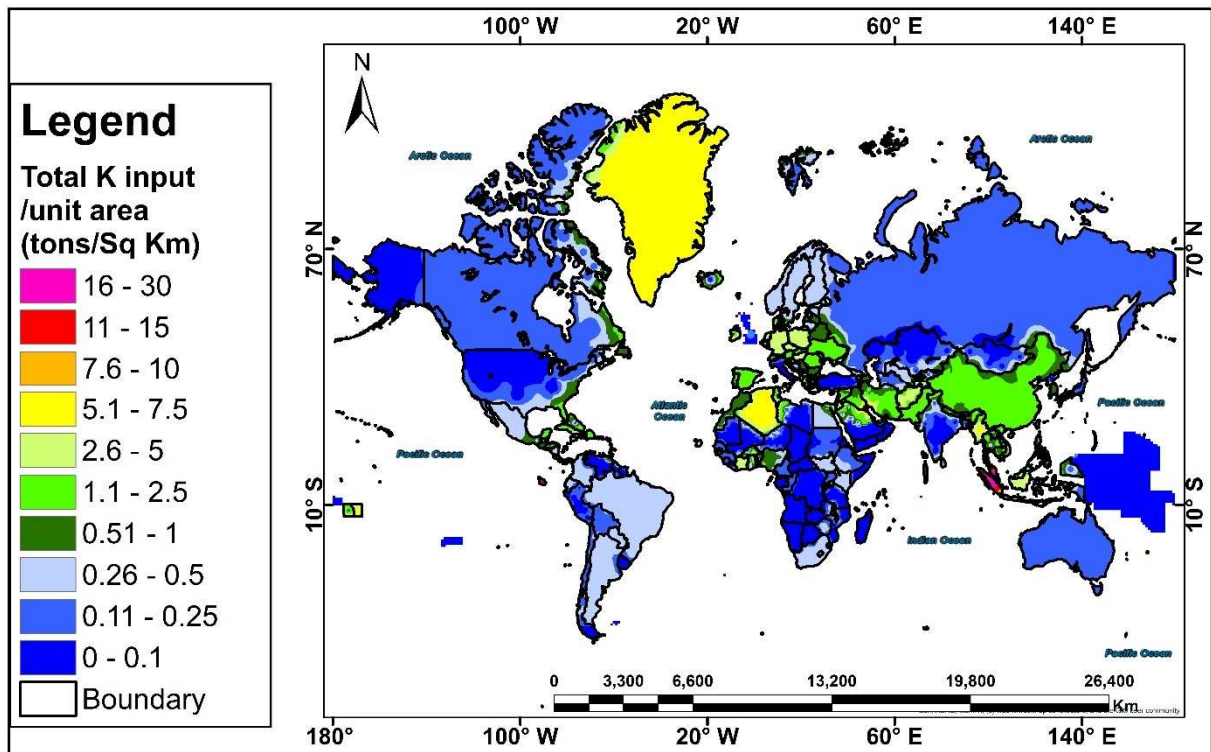
270 Figures 1-3 summarise the state of potassium demand and deficiency globally. Considering
271 population growth and distribution (UN, 2018 population data), the demand for increased
272 volumes of food supply will come from Asia, North America, South America, then Europe
273 and Africa in that decreasing order. As South Asia and Europe are more densely populated,
274 these regions would require more fertiliser input per unit area. Figure 1 shows that by 2001
275 most soils worldwide were depleted in K. This means almost all countries globally need K
276 inputs to replenish their soil K depletion, which can mainly be attributed to soil mining
277 through crop growth. Greater focus needs to be on the more populous regions of Asia.
278 Africa's population has also been increasing at alarming rates and is expected to double from
279 1.1 billion in 2010 to close to 2 billion in 2040, Therefore more efforts are also needed to
280 increase K fertiliser inputs in African soils.



281
 282 **Figure 1.** Annual soil potassium nutrients balance per hectare per year for globally, in tonnes
 283 from input, uptake and depletion from all sources. *Source:* Using data from Sheldrick (2001).

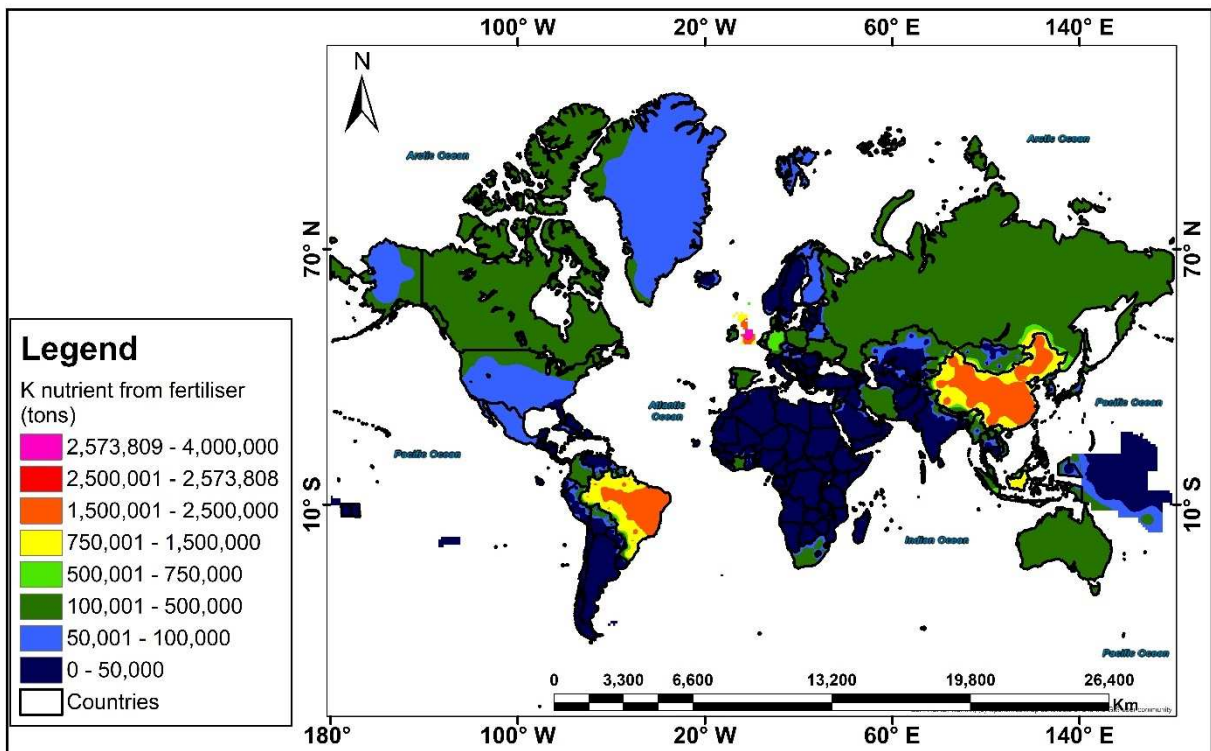
284

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



294
295
296

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).



297
298
299

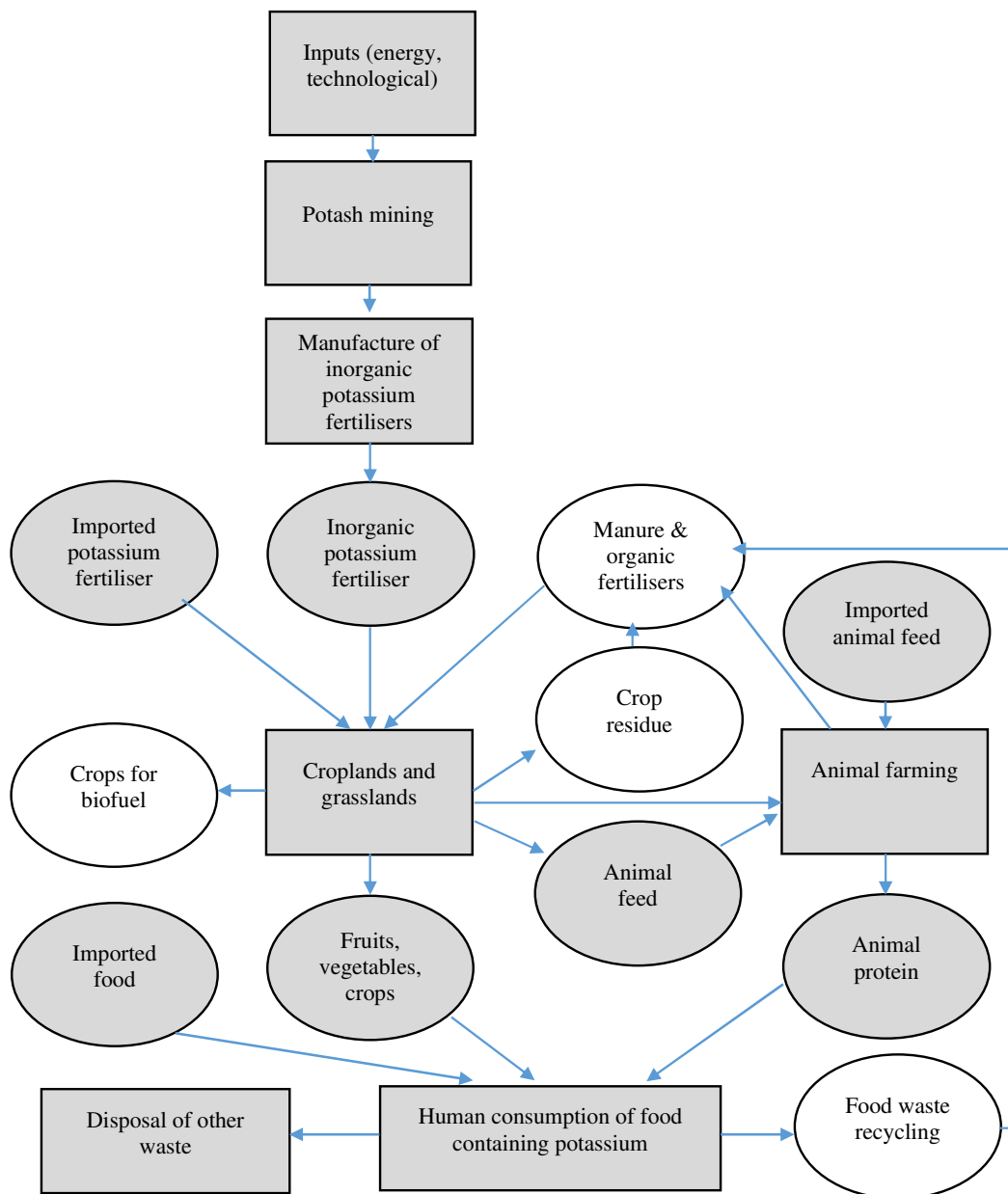
Figure 3. Potassium nutrients from commercial fertilisers input into the soil by farmers per country (in tonnes). *Source:* Using data from Sheldrick (2001).

300

301

302 **4.2. Six approaches to improving supply of potassium fertilisers in developing**
 303 **countries**

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



308

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

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

326 *4.2.1. Expand traditional production: search for conventional potash mineral deposits*

327 The traditional approach is to expand conventional potash production and develop mines in
328 the Global South that would form a supply basis for regional potassium fertiliser production.
329 However, almost all potash (this term refers to a number of different mineral salts that contain
330 potassium³) is mined in just 8 countries: Canada, Russia, Belarus, and Israel, followed by

³ Potash is mined in various forms: potassium chloride (KCl or muriate of potash), potassium sulphate (K₂SO₄), potassium–magnesium sulphate (K₂SO₄ 2MgSO₄), and potassium nitrate (KNO₃) (Al Rawashdeh and Maxwell, 2014; USGS, 2009). The mineral polyhalite (K₂Ca₂Mg(SO₄)₄·2H₂O) is a new multi-nutrient product (14% K₂O; 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 (K₂O) equivalent. About 93% of the world’s mined potash is used by the fertiliser

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

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

industry (USGS, 2009).

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%

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

357 Note: 2015e – estimated output for 2015.

Country	Recoverable ore	K ₂ O 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

358 **Table 3:** Global reserves of potash, thousand metric tonnes. *Source:* US Geological Survey
359 (2016).

360 Note: n/a – data not available.

361

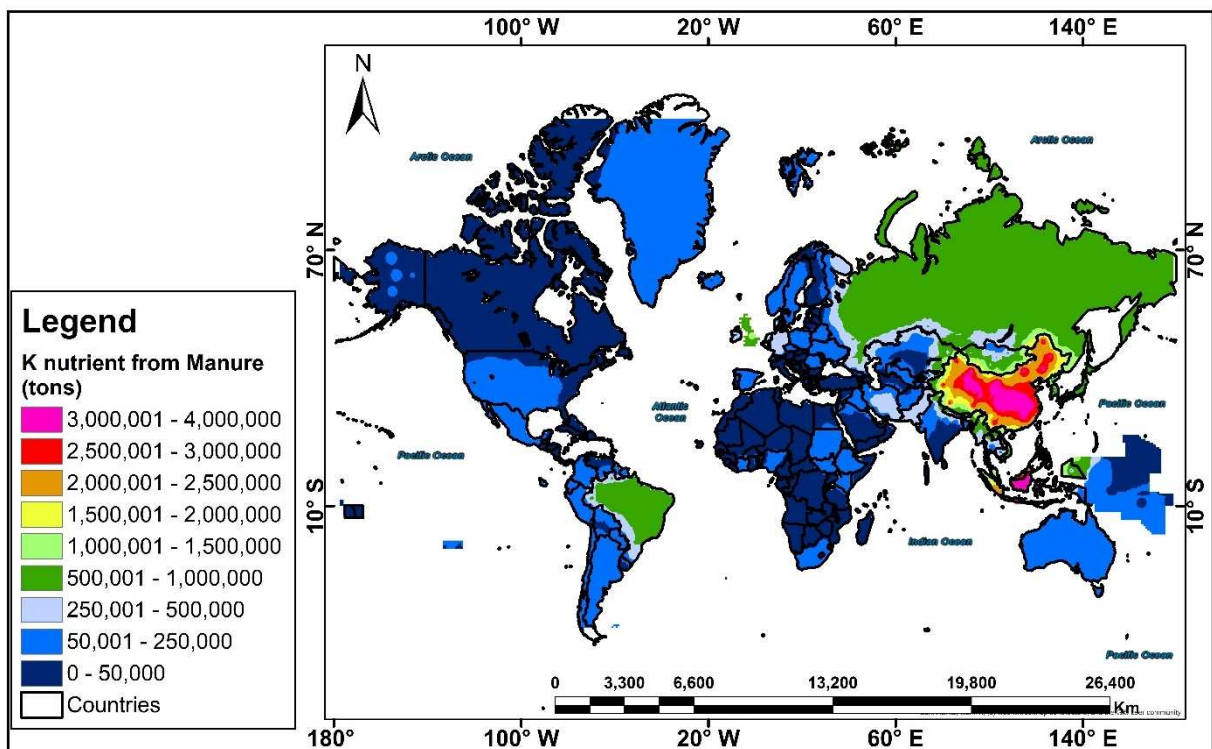
362 *4.2.2. Find new mineral sources: Search for alternative sources of potash*

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

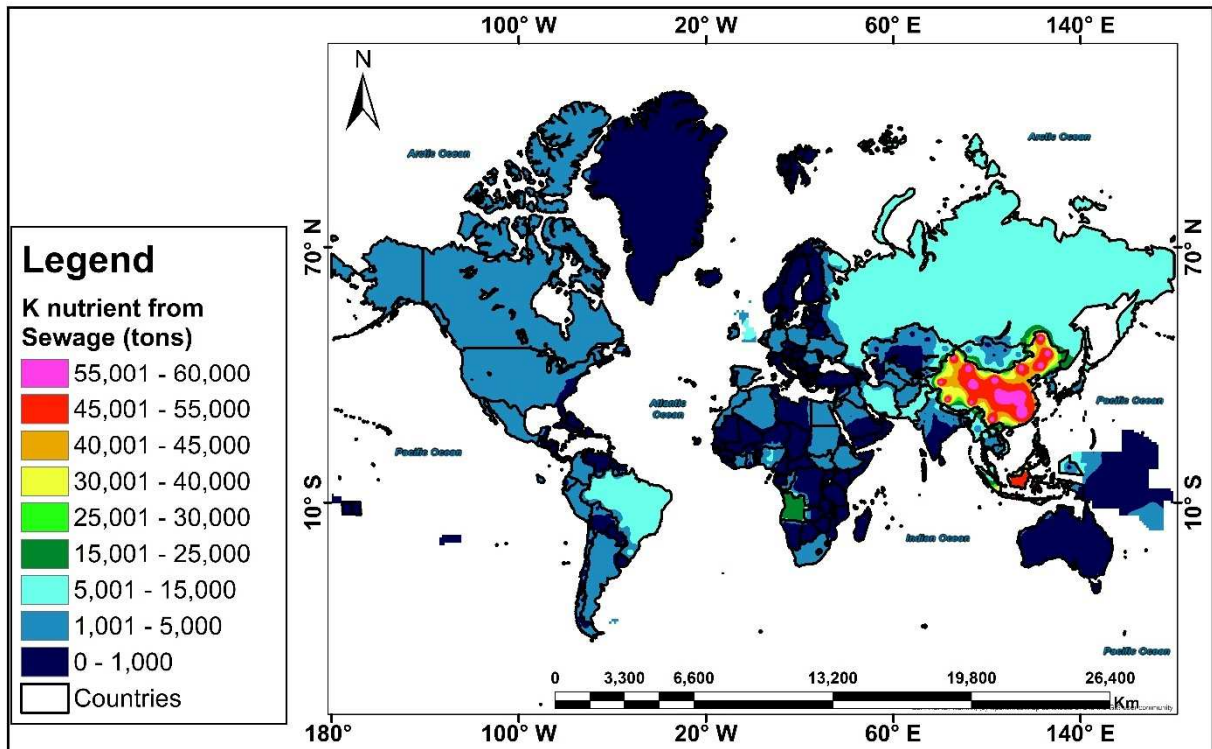
374 Given that the indigenous agricultural systems in the Global South maintained soil quality and
375 food production previously, Leonardos et al. (2000) support propositions for small-scale
376 agriculture that combine the use of inorganic or mineral fertilisers (such as phosphate or
377 silicate rock) with organic sources of nutrients for plant growth. In the context of the Global
378 South, Leonardos et al. (2000) promote an idea of using locally sourced fertilisers to support
379 subsistence and modern agriculture, bearing in mind that the majority of farm units are small
380 (in Brazil, only 10% of farm units produce the commodity crops that Brazil is famous for, and
381 90% produce crops for domestic consumption (Manning and Theodoro, 2020). In such cases,
382 the ‘stone meal’ can be provided at low cost by local producers and small-scale miners; the
383 use of these materials is now embedded in Brazilian federal law through the regulation of
384 ‘remineralizers’ (Manning and Theodoro, 2020).

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

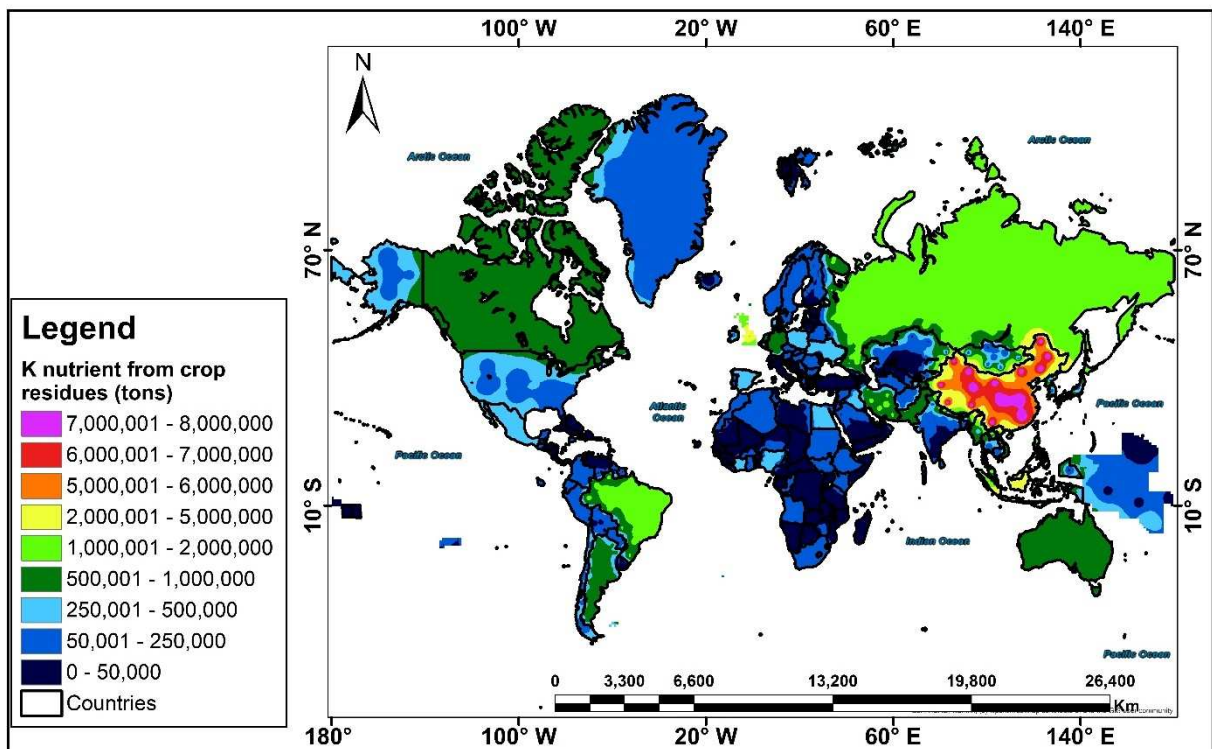
386 of potassium should be encouraged, as conventional soluble potassium fertilisers are not
 387 entirely appropriate for soils in tropical and sub-tropical zones. In many cases, the use of
 388 crushed rock as a remineralizer embeds a circular economy concept; many mines and quarries
 389 that produce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



398
 399 **Figure 5.** Potassium nutrients from manure input into the soil by farmers per country (in
 400 tonnes). *Source:* Using data from Sheldrick (2001).



401
 402 **Figure 6.** Potassium nutrients from sewage input into the soil by farmers per country (in
 403 tonnes). *Source:* Using data from Sheldrick (2001).



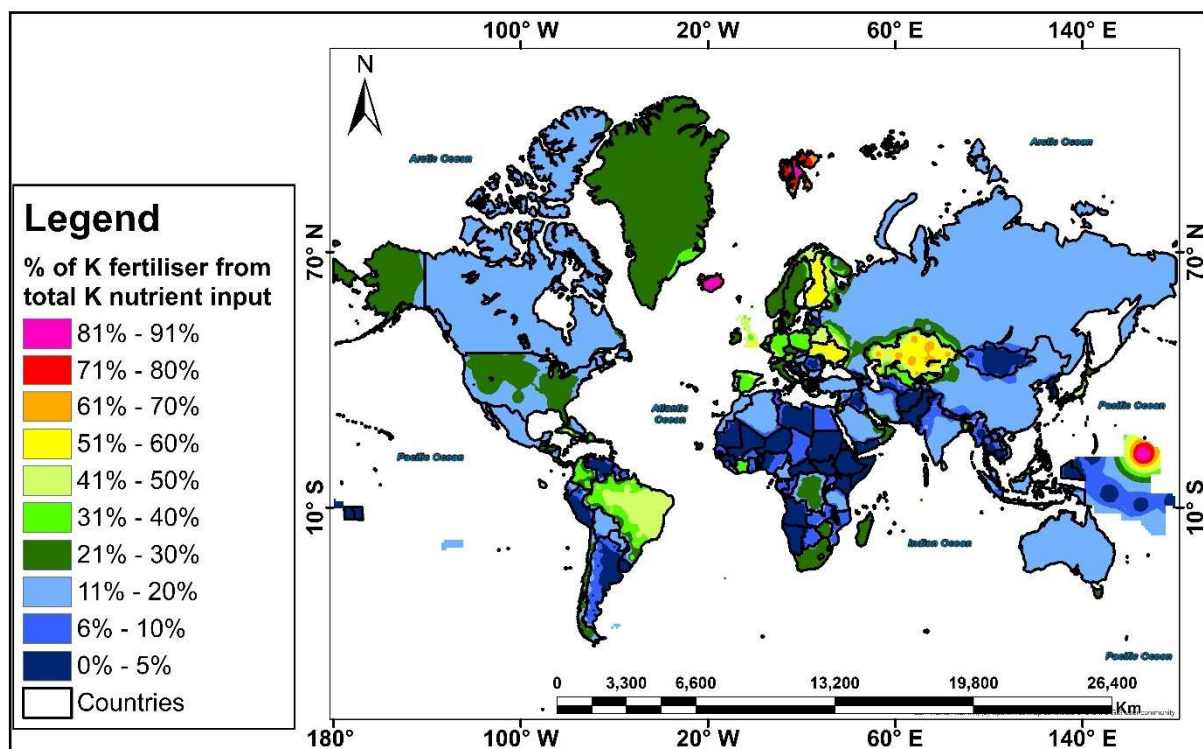
404
 405 **Figure 7.** Potassium nutrients from crop residues input into the soil by farmers per country (in
 406 tonnes). *Source:* Using data from Sheldrick (2001).

407

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

415 *4.2.3. Improve markets: support of potassium fertiliser trade in developing countries*

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



428
 429 **Figure 8.** Percentage of potassium fertiliser over total input into the soil by farmers per
 430 country (in tonnes). *Source:* Using data from Sheldrick (2001).

431

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

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

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

451 There have been many policy changes in most sub-Saharan African countries, including the
452 liberalisation of agricultural input and output markets. One example of these was the
453 Structural Adjustment Programmes, through which governments stopped controlling prices of
454 fertilisers. This enabled the private sector to take control over fertiliser markets (Marquis et
455 al., 2013). Several policies have been implemented following the New Partnership for Africa's
456 Development (NEPAD) of the African Union with the view of promoting fertiliser demand
457 and supply (Marquis et al., 2013). One such initiative was the opening of the region to allow
458 fertiliser supply. For example, Ethiopia opened up for investment in the fertiliser
459 manufacturing industry including granting a mining concession to the Allana Potash
460 company, which sought to produce 1 million tonnes/year of muriate of potash (MOP) at their
461 Danakhil mine. The DRC has also attracted investment for the Sintouka potash project from
462 Australia to develop a mine in the DRC, which was expected to begin production of 1.8
463 million tonnes/year by 2015 (Marquis et al., 2013), although this has been delayed (USGS,
464 2019).

465 Another policy decision that has been made in many African countries is the strengthening of
466 the agro-dealer sector to improve the quality of their service delivery. This was done to
467 increase sales and access to the local farming communities. These initiatives included
468 providing credit guarantees and loans to the upcoming agro-dealers so that they can import

469 and distribute fertilisers more easily. For example, in Kenya, Rwanda, Burundi, Tanzania,
470 and Ghana, a not-for-profit organisation called the One Acre Fund offers loans for fertiliser
471 and seeds to local farmers with a minimal interest repayment, which is used to cover
472 operational costs.

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

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

494 In addition, Ott (2012) adds that the farmgate fertiliser price is controlled by various factors
495 including the synergies between demand and supply which are further subject to world
496 economic factors, such as transport costs, raw materials, and commodity prices, as well as
497 population growth. For example, Malawi's geographic location as a land-locked country
498 greatly contributes to higher fertiliser costs than in neighbouring countries such as Tanzania
499 and Mozambique. Malawi relies on three major seaports, namely Nacala and Beira
500 (Mozambique), Dar es Salaam (Tanzania), and to some extent Durban (South Africa).
501 Marquis et al. (2013) observed that this problem is also faced by other sub-Saharan African
502 countries, thereby increasing the prices of fertilisers to US\$200/tonne higher than free on
503 board (fob) prices on the global markets. Therefore, additional costs apart from the purchasing
504 prices also originate from importation through neighbouring countries' ports. Transport costs
505 from the port to Malawi's capital, Lilongwe, where the fertiliser is delivered, blended, and
506 redistributed countrywide, are US\$50 to >US\$200 per tonne.

507 *4.2.4. Reduce: reduce inorganic fertiliser use by increasing organic fertiliser use in large-*
508 *scale food production*

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

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

529 *4.2.5. Reuse: reuse organic and inorganic fertiliser in close-cycle agricultural systems*

530 Currently, there are constrained applications of potassium recycling. Potassium follows a one-
531 way stream from extraction to use in agriculture, consumption, and disposal ultimately via
532 river drainage systems into the ocean. Potassium can be applied to soil not only from mineral-
533 based fertilisers, but also from manure, crop residue, and compost (Sheldrick and Lingard,
534 2004; PDA, 2008; DEFRA, 2010; Dawson and Hilton, 2011; Elser and Bennett, 2011). To
535 maintain soil quality, methods such as agroforestry can be used (Binam et al., 2014). Studies
536 acknowledge that due to minimal use of commercial fertilisers and increasing agroforestry
537 techniques, small-holder farmers can improve soil quality through the utilization of green
538 manure and compost (Binam et al., 2014).

539 For organic farming, conventional chemical fertilisers are not used, and nutrient management
540 focuses on nutrient recycling through integrated management of crop and livestock production
541 (Nowak et al., 2015). Importantly, these practices promote local mass flows, exchanging
542 materials from livestock to crop production and designing a holistic approach to farming at a

543 local level to maintain soil quality and enhance food production (PDA, 2008; Nowak et al.,
544 2015). Organic farming actively uses mined potassium fertilisers, which are acceptable where
545 need can be justified, providing their production avoids chemical processing (Soil
546 Association, 2003; PDA, 2008). There are clear opportunities for promoting integrated
547 farming systems in developing countries and engaging with organic farming principles.

548 *4.2.6. Recycle nutrients: recycle farming and food waste for fertiliser production*

549 Studies on recycling and recovery of nutrients from food waste or the animal food chain
550 suggest promising recovery rates of valuable NPK nutrients and reapplication for food and
551 crop production (Zheng et al., 2020). Advancement of nutrient recycling technologies from
552 farming waste can aid in closing the loop for nutrients and reduce the loss of nutrients
553 (Jurgilevich et al., 2016). However, because of natural losses (given that soil is an open
554 system), inorganic fertilisers cannot be fully replaced with recycled nutrients, but supplement
555 the recovery of nutrient material (see Bai et al., 2016). Elser and Bennett (2011) report that
556 valuable nutrients, potentially usable in agriculture, are lost with food waste; and as much as
557 40% of food is wasted by households in developed countries (Mirabella et al., 2014).
558 Capturing the nutrients from composting of food waste presents another route for recycling
559 potassium for farming. Recycling food waste in developing countries, especially in populous
560 urban areas, can be added to nutrient recycling that supplies peri-urban farming. Here,
561 technologies around anaerobic digestion and valorisation of food waste with the participation
562 of food retailers could prove useful (Ng et al., 2019).

563

564 **5. Discussion**

565 Based on the study of potassium supply, we identify three main challenges to the

566 implementation of circular economy principles in developing countries: technological,
567 market, and institutional factors. Our research adds to the growing body of research on
568 barriers to circular economy implementation (Upadhyay, 2021b).

569 Firstly, in the context of technology, although advancement of mineral exportation and
570 production, as well as improvement of farm and waste techniques to improve recovery at farm
571 level, are ongoing, there is still room for improving the recycling of nutrients from agriculture
572 and scaling up these technologies for availability to farmers in the Global South. Tilton et al.
573 (2018) suggest that support of new technologies and innovation is the paramount solution to
574 short and long-term shortages of resources, as this solution can enhance efficiencies of
575 primary production and recycling and develop substitutes to existing resources.

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

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

587 To address the three challenges, the six approaches proposed in our research provide a
588 structure for policy formulation and can be used in combination. These approaches integrate
589 two major paradigms of modern food production, one that relies on industrialised agriculture

590 and depends on large-scale mono food production and the second that promotes small-scale
591 food production and relies on a combination of farm practices and encourages amongst others
592 organic production (Sonnino and Marsden, 2006). These conventional and alternative agri-
593 food systems both have a place in developed countries and thus potassium fertilisers supply
594 should adjust to the evolving food production patterns (Manning and Theodoro, 2020).

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

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

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

629

630 **6. Conclusions**

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

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

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

650

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