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Discussion

Local fertilizers to achieve food self-sufficiency in Africa

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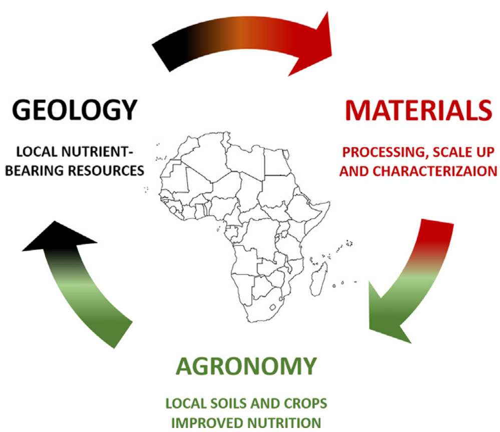
GRAPHICAL ABSTRACT



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ABSTRACT

One of the key Sustainable Development Goals (SDG) set by the United Nations (UN) aims by 2030 to "*end hunger, achieve food security and improved nutrition and promote sustainable agriculture*". Fertilizers will play a pivotal role in achieving that goal given that ~90% of crop production growth is expected to come from higher yields and increased cropping intensity. However, materials-science research on fertilizers has received little attention, especially in Africa. In this work we present an overview of the use of fertilizers in Africa to date, and based on that overview we suggest future research directions for material scientists. Developing a new generation of local and affordable fertilizers will launch Africa into a new phase of remunerative agricultural production that in turn will lead to both food self-sufficiency and considerable progress towards goals of food and nutrition security.

1. Introduction

As of 2018, food security remains a key global challenge. According to the Food and Agriculture Organization of the United Nations (FAO) an estimated 815 million people are currently suffering from

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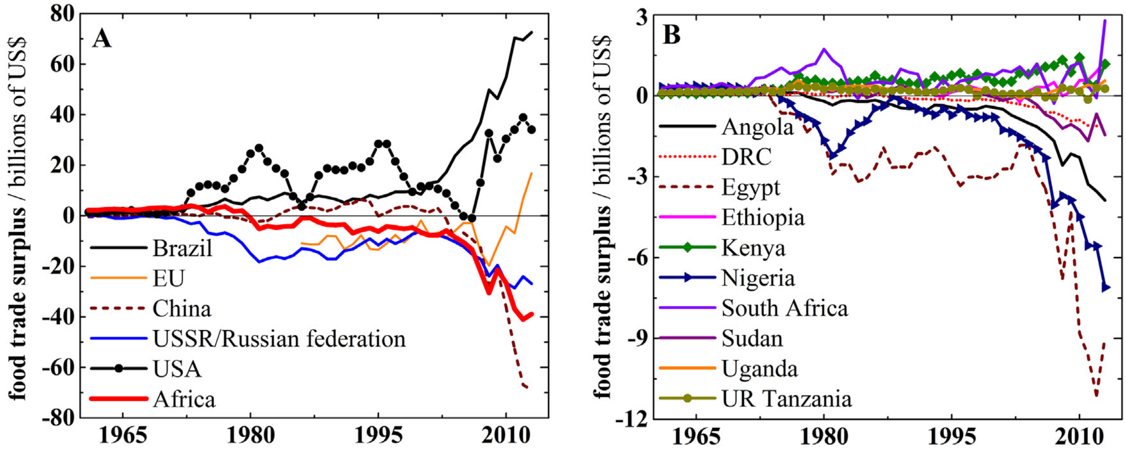

Fig. 1. Value of food trade surplus (food exports minus food imports) in billions of US$ for (A) selected countries or regions and (B) the ten African countries forecast to have the largest population in 2050. EU data starts in 1986 and refer to extra-EU trade only; Ethiopia data starts in 1993; USSR data are up to 1992 and continued with Russian Federation data; *former Sudan* (up to 2011) and *Sudan* are shown simply as Sudan.
Source: FAOSTAT.

undernourishment (FAO, 2017a). Africa is the continent with the highest number of undernourished people with respect to total population, although the highest absolute number is found in Asia (519.6 M). In 2014, undernourishment as high as 55% was reported for the Central African Republic (CAR), followed by 46% for Zambia and ~41% for Zimbabwe and Liberia. The continent-wide average corresponded to ~18%, equivalent to 209.5 million people (Supplementary Material S1).

Root causes that generate undernourishment in Africa include diffuse poverty and conflicts, failed states, a changing climate, malnutrition and a generally low agricultural productivity (AAVV, 2001; FAO, 2017b; Sasson, 2012). Additionally, a key complicating factor is the continuing and rapid population growth originating from both improved public health and a limited approach to family planning (Bongaarts and Casterline, 2013). Africa will contribute to ~58% of the world population growth to 2050, and will host by then ~2.5 billion people, roughly a fourth of the world population. Nigeria will top by far any other African country with an expected 410.6 M people, followed by the Democratic Republic of Congo (DRC) (197.4 M) and Ethiopia (190.9 M). The largest rural population will be concentrated in Nigeria (144.9 M), Ethiopia (117.1 M) and Uganda (70.7 M) (Supplementary material S1).

To tackle such a massive demographic change no single solution is available and innovative approaches to food production will have to be found. One area of relative consensus is that *local* food production will need to increase substantially, to reduce or at least maintain current food prices in a context of rapidly increasing demand. Currently, Africa imports ~40% of the food value consumed (FAO, 2017c; Rakotoarisoa et al., 2011; Sasson, 2012), in net contrast with the comparative advantage that derives from the combined availability of both land and a young workforce (Fig. 1A). Food imbalances between rural and urban areas are also reported (Rakotoarisoa et al., 2011). Reliance on foodstuff imports is not necessarily an issue if it is due to an economy that specializes in services or high-value goods. However, that is not the case for most African countries, which should strive for food self-sufficiency to become less susceptible to shocks in foreign-food supplies and to avoid purchasing international currency for payment of food imports (Marchand et al., 2016; van Ittersum et al., 2016). Among countries with the largest population forecast, Egypt, Nigeria and Angola face the most substantial food deficit whereas Kenya, Ethiopia and South Africa the most substantial food surplus (Fig. 1B).

Fertilizers are important agricultural inputs at the base of the concept of food self-sufficiency, and will play a vital role in transforming African agriculture, although they may still be insufficient to feed Africa (AAVV, 2001; FAO, 2017b; Pradhan et al., 2014; Pradhan et al., 2015; Stewart and Roberts, 2012; van Ittersum et al., 2016; Vlek, 1990). Over the next 30 years, global food-production increases between 28% and 58% could be obtained alone by closing local yield gaps across the globe (Foley et al., 2011; Pradhan et al., 2014; Pradhan et al., 2015), with the future role of fertilizers evidenced by the fact they will be responsible for about 30%–50% of that expected yield

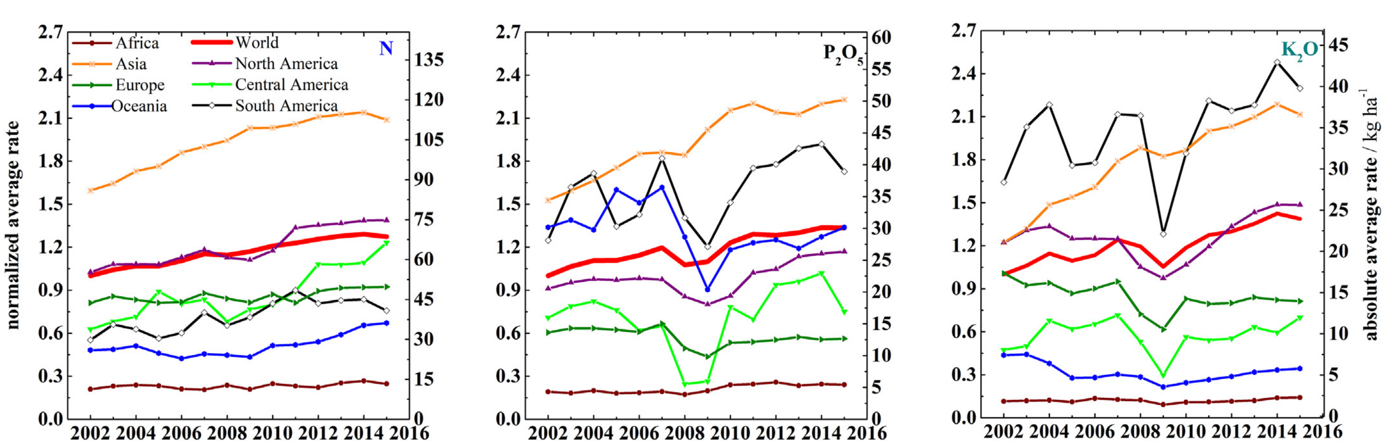

Fig. 2. Average fertilizer use (kg nutrient ha^{-1} cropland) per geographical area. Left axis is the normalized value to the world average in 2002; right axis is the absolute value.
Source: FAOSTAT.

increase (Stewart et al., 2005; Stewart and Roberts, 2012). A sound use of fertilizers faces several challenges in Africa, as demonstrated by chronically low rates of application in the field (Fig. 2). Several countries including those cornered in ongoing crisis such as Somalia and South Sudan reported no use of NPK nutrients at all (Supplementary material S1). Limitations that hampers the use of fertilizers in Africa are well known and often discussed within a logic of demand and supply, according to a framework provided by economic disciplines (AAVV, 2016; Chianu et al., 2012; Druilhe and Barreiro-Hurlé, 2012; El-Fouly and Fawzi, 1995; FAO, 2017b; Foley et al., 2011; Godfray et al., 2010; Hernandez and Torero, 2011, 2013; "Intelligence Community Assessment. Global Food Security,", 2015; The political economy of Africa's burgeoning chemical fertiliser rush, 2014; Liverpool-Tasie et al., 2017; Minot and Benson, 2009; Rakotoarisoa et al., 2011; Sasson, 2012; Sheahan and Barrett, 2017; Vlek, 1990). A key difference should be drawn between *potential* and *actual* demand. For example, one could consider the application rate per area of cropland in the EU (139.76 kg_{NPK} ha^{-1}) or in the USA (133.4 kg_{NPK} ha^{-1}), and imagine it to be the desired target for Africa too. Those rates would correspond to 26.1–27.6 M t of combined $N + P_2O_5 + K_2O$, assuming an arable land of 234,950,710 ha (FAO, 2017c). For comparison, the amount of fertilizer produced in the EU and in the USA in the same year was 17 M t and 22 M t, respectively. Therefore, the potential demand is massive in Africa, even when obvious differences between industrial and subsistence agriculture are considered. In reality the actual demand confronts critical barriers, above all that commercial fertilizers pay minimal dividends for most subsistence farmers (Liverpool-Tasie et al., 2017). The global fertilizer industry is dominated by few overseas producers (Hernandez and Torero, 2013), and the local price of the fertilizer remains unaffordable, partly because of a largely inadequate inland infrastructure and consequent high cost of transportation from distant production sites to African farmers (Morris et al., 2007). Additional factors that contribute keeping the fertilizer actual demand depressed include the farmers' skillset, which may not be sufficiently advanced to allow a proper implementation of the 4R principle (right source, right rate, right time, right place) (Bindraban et al., 2015; Johnston and Zingore, 2013), the general inability to finance fertilizer purchases and the poor and/or scattered information about seasonal availability of the fertilizer. On the *supply* side, a crucial issue is that Africa currently lacks opportunities for economies of scale. Private investments in fertilizer manufacturing and distribution are discouraged by an environment adverse to business because of the small, weak and dispersed actual demand. Concurrently, unfavorable food trade terms (Fig. 1) and an inefficient distribution system prevent the development of a local food market, with the cost of local food crops remaining high with respect to those imported (AAVV, 2001; Bureau and Swinnen, 2017). A new approach would be for Africa to resort to local natural resources such as agrominerals, soils and indigenous crops as the base of food production, similarly to consumers in the developed world that are increasingly moving towards a local approach (Michelson, 2017; Sánchez, 2010; van Straaten, 2011). This implies developing new fertilizer materials with a supply chain centered on African conditions. As an example, standard nitrogen (N) products such as urea are not necessarily suited for Moroccan alkaline soils where they would generate ammonia (NH_3); phosphorous (P) products are likely to dissolve much faster in the acidic soil of the DRC than elsewhere in Africa; soluble potassium (K) products can be easily leached in the tropical belt of Africa, where it is commonly but erroneously assumed that K is rarely limiting (Manning, 2017; van Straaten, 2011). The reactivity of the fertilizer varies with the soil type, and indeed the crop response to fertilizers changes significantly across Africa, partly because of differences in soil physicochemical properties. The response coefficient for sorghum with standard fertilizer products has been reported to be 16.3 kg of yield per kg of fertilizer in Ethiopia, approximately twice the value reported for Ghana and Togo (Taddese, 2001). These findings exemplify the need to develop an understanding of the reactivity of fertilizers

Table 1
Overview of major soils and crops for both Africa as a continent and for the ten African countries with the largest population forecast to 2050 (Supplementary Material S1) (Bationo et al., 2012; FAO, 2017c; Hengl et al., 2017; Jones et al., 2013; van Straaten, 2011; van der Waals and Laker, 2008).

	Soils	Crops
Africa	Lithosols (40.3%), arenosols and regosols (18.7%), acrisols and ferrasols (16.2%), cambisols (6.8%), andisols and nitosols (3.8%), other (13.3%)	Bananas and plantains, cassava, citrus, maize, oil palm, potatoes, rice, sorghum, sugar beet, sugarcane, sweet potatoes, tomatoes and vegetables, wheat, yams
Nigeria	Acrisol, cambisols, luvisol, regosols	- Cassava, cocoyam, cowpea, maize, millet, rice, sorghum, yam - Cocoa, cotton, ginger, groundnuts, oil palm, sesame
DR Congo	Acrisols, arenosols, ferrasols, podzols, regosol	- Bananas and plantains, cassava, groundnuts, maize, rice, sorghum - Cocoa, coffee, sugarcane, palm trees, rubber, tobacco, tea
Ethiopia	Andosol, cambisols, nitisols, vertisols	- Cereals (barley, maize, millet, sorghum, tef, wheat), oilseeds, pulses, roots and tubers, vegetables - Coffee
Egypt	Arenosols, calcisols, fluvisols, leptosols, regosols, solonetz, vertisols	- Cereals (maize, rice, wheat) - Cotton, fruits (citrus and grapes), sugar beet, sugarcane, vegetables
UR Tanzania	Acrisol, cambisol, ferrasol, leptosol, lixisol, luvisol, nitisol, vertisol	- Bananas and plantains, beans, cassava, maize, millet, potatoes, rice, sorghum, wheat - Cashew, cloves, coffee, cotton, flowers, oilseeds, sisal, spices, tea, tobacco
Uganda	Ferralsol, luvisol, nintisol, vertisol	- Bananas and plantains, maize, millet, potatoes, pulses, rice, sorghum, wheat
Kenya	Acrisols, andisol, ferralsols, lixisols, luvisols, nitisols vertisols	- Bananas, maize, potatoes, pulses - Coffee, flowers, fruits, tea, vegetables
Sudan	Arenosol, entisoil, vertisol	- Cereals (barely, maize, millet, sorghum, wheat), fruits (citrus, dates, yams), vegetables - Coffee, cotton, cottonseed, peanuts, sesame, sugarcane, tobacco
Angola	Arenosol, ferralsol	- Maize, potatoes, rice - Coffee, cotton, sugarcane, tobacco
South Africa	Acrisol, arenosols, calcisols, cambisol, lithosols, vertisol	- Maize, potatoes, soybeans, wheat - Sugarcane

applied to local soils (Bindraban et al., 2015). An overview of the key soil types and crops of Africa is provided in Table 1. Historically, physicochemical data for African soils have been limited or at least inaccessible by the global community, although recent developments are addressing that gap (Table 1) (Hengl et al., 2017; Kihara et al., 2017; Sánchez, 2010; Tully et al., 2015).

Materials science discoveries could contribute significantly to develop a holistic approach to African agriculture and overcome both economic and soil limitations. However, they are rarely discussed in the literature. Therefore, this work focuses on the role that fertilizers will play in achieving food self-sufficiency in Africa from the perspective of the materials scientist, confronting some constraints of the global commodity market with technical advances. First, we briefly summarize the broader policy framework and examine fertilizer trade and use in Africa. Second, we propose a research agenda on fertilizer materials that will benefit African agriculture. We recognize the critical importance of

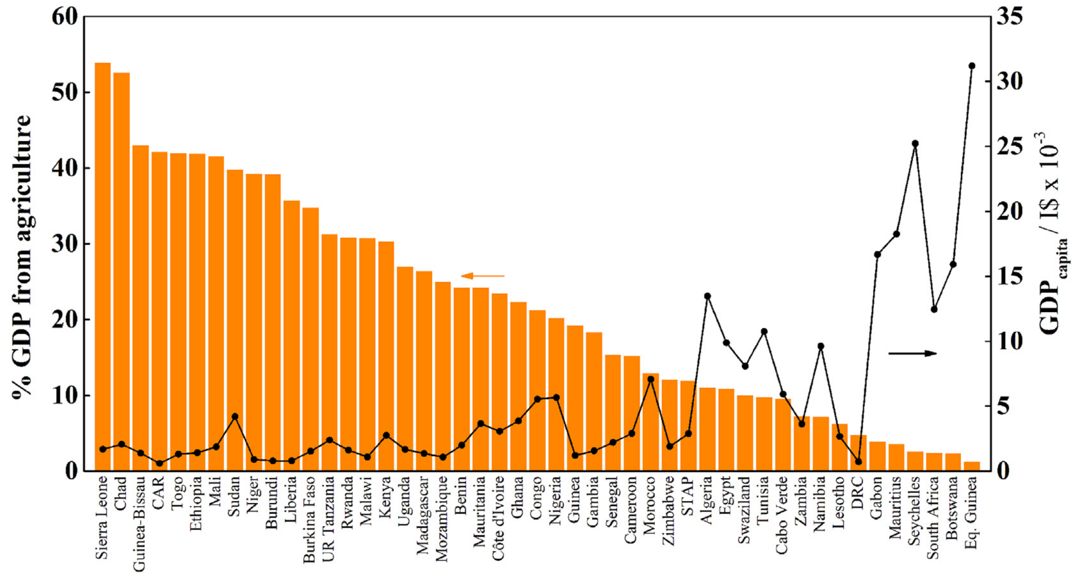

Fig. 3. Comparison between percentage of the GDP due to agriculture and GDP *per capita* in international dollars (Supplementary Table S1); no data available for Angola, Comoros, Djibouti, Eritrea, Libya and Somalia.
Source: International Monetary Fund (IMF) and World Bank.

variables other than the fertilizer such as water availability and governance (FAO, 2017b; Godfray et al., 2010; Pradhan et al., 2014; Sasson, 2012; van Ittersum et al., 2016), and acknowledge the need for an integrated approach based on information on smaller spatial scales than those continental or national used here (Liverpool-Tasie et al., 2017; Michelson, 2017; Sheahan and Barrett, 2017). Progress has occurred in recent years, for example the increased share of both public and private investments in the agricultural sector (AAVV, 2016), and we show additional opportunities for local development. By anticipating the constraints that population growth and climate change will impose on African agriculture, the multidisciplinary strategy outlined in this work permit to devise local and sustainable technologies to manufacture affordable, green and smart fertilizers, which will all be critical to the agricultural success of Africa in the short timeframe to 2030.

2. Materials and methods

All data discussed in this manuscript are obtained from either FAOSTAT (FAO, 2017c) or the World Fertilizer Outlook (*World Fertilizer Trends and Outlook to 2018,* 2015). Fig. 3 was built from data available online through the International Monetary Fund and the World Bank. Data on soil nutrient mining reported in Fig. 5 are calculated from agricultural production tonnage for each of the selected crops for the year 2014 (FAO, 2017c) and assuming as the P_2O_5 and K_2O content in each of the crops the value provided by the USDA Food Composition Databases ("USDA Food Composition Databases"). Data for sugar cane composition are obtained from Sing and Lal (Singh and Lal, 1961).

3. Results and discussion

3.1. Overview of fertilizer use in Africa: policy and trade

Africa is a landmass of 30,370,000 km^2, host of 54 fully recognized sovereign countries, and spanning a wide range of climatic conditions, landscapes and cultures. Overarching development objectives within such complexity are provided by the Sustainable Development Goals (SDG) of the UN. SDG 2 aims to "*end hunger, achieve food security and improved nutrition and promote sustainable agriculture*". Key publications such as *The State of Food Security and Nutrition in the World* summarize an extensive set of global data monitoring progress towards that objective (FAO, 2017a). Here, we limit the scope to a brief overview of agricultural and fertilizer policies, attempting to individuate how they are linked to food self-sufficiency. Comprehensive reviews can be found elsewhere (AAVV, 2016; Bureau and Swinnen, 2017; FAO, 2017b; Glauber and Effland, 2016; Juma, 2011; Morris et al., 2007). As shown in Fig. 3, in Africa the share of the GDP due to agriculture is anti-correlated to the GDP *per capita*, and among the richest countries only Egypt, Algeria and South Africa show a strong agricultural production (Supplementary material S1). Other high-GDP countries such as Equatorial Guinea, Gabon and Botswana rely on economies largely based on the extraction of oil and/or mineral commodities rather than agriculture (Supplementary material S1). Providing the broader policy framework that regulates agricultural production and trade at international level is therefore key to develop an African fertilizer industry.

3.1.1. Agricultural and fertilizer policy

A first important policy with consequences on Africa is the Common Agricultural Policy (CAP) of the European Union (EU) (Bureau and Swinnen, 2017; Juma, 2011). In the 1980s–1990s the EU has made widespread use of both internal subsides and tariffs on imported food, which in turn have led to significant export of European surpluses to Africa. This has been seen as an external factor that prevented Africa from achieving its potential agricultural output (AAVV, 2001). CAP has undergone major reforms over the years, and several initiatives have been implemented, for example *Everything But Arms*, a broad duty-free trade policy that now promotes fairer EU-Africa trade. However, areas of criticism still exist such as exceedingly strict environmental and quality certifications imposed by the EU on imported food, including organic food (Bureau and Swinnen, 2017; Willer et al., 2013). Agricultural policies in the USA have not benefited Africa either, with large amounts of USA food surpluses shipped in the form of aid in the past (AAVV, 2001; Glauber and Effland, 2016). This has changed, but protective policies are still in place, although regulated (Glauber and Effland, 2016). Over the past decade China has also increased its interest in Africa, launching intense investments program in infrastructure in exchange for mineral resources and non-food agricultural products such as timber. With China now entering into a period of food deficit (Fig. 1) numerous agricultural land purchases and land loans from Chinese investors in Africa have also been reported. In this international context African agriculture has remained scarcely remunerative, although it is widely acknowledged that agriculture still remains the

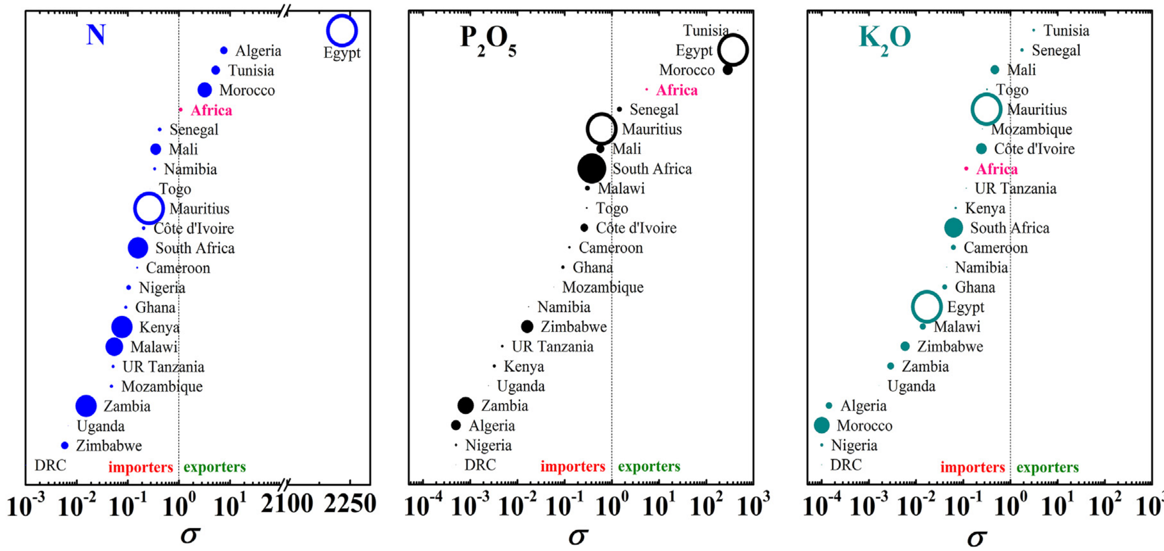

Fig. 4. Overview of mineral fertilizers export-to-import weight ratios (σ) in 2014 for selected African countries. The size of the bubble is the average nutrient application rate in kg of nutrient per ha of cropland. For reference data for South Africa are 35 kg N ha^{-1}, 18 kg P_2O_5 ha^{-1}, 10 kg K_2O ha^{-1}. Empty bubbles are not to scale (Egypt: 366 kg N ha^{-1}, 116 kg P_2O_5 ha^{-1}, 16 kg K_2O ha^{-1}; Mauritius: 126 kg N ha^{-1}; 43 kg P_2O_5 ha^{-1}; 101 kg K_2O ha^{-1}). Bubble size is not to be compared across nutrients. Here, Africa refers to the pool of selected countries. Data do not account for biomasses. Actual data are reported in Supplementary material S3.

most viable sector to promote local sustainable development (Juma, 2011). This is recognized for example by the Global Food Security Act (GFSA) of the USA government, for which a key pillar focuses on inclusive and sustainable agricultural-led economic growth ("U.S. Government Global Food Security Strategy 2017-2021,", 2016). The key importance of agriculture is recognized also by one of the major active policy within Africa, *i.e.* the *Comprehensive Africa Agriculture Development Programme* (CAADP). Established in 2003, CAADP sets two key goals for each African country: achieving a 6% annual growth in agricultural GDP and allocating 10% of public expenditure to agriculture (Juma, 2011).

Fertilizers are critical to both achieve CAADP goals and outcompete the EU and USA food markets. This critical role of fertilizers was explicitly affirmed with the Abuja declaration of 2006 which stated the intention of the African Union (AU) members to raise the continent-wide rate of fertilizer application to 50 kg ha^{-1}. Some initiatives followed such a declaration (Morris et al., 2007). As an example, the African Development Bank (AfDB) has launched financing programs to promote scalability of fertilizer pilot schemes, increase business opportunities along the fertilizer value chain, finance large-scale fertilizer operations and assist with regulations. However, most of these and other initiatives were delayed, and the prefixed fertilizer rate has not yet been achieved (Fig. 2). For example, Sierra Leone, Chad and Guinea-Bissau that are the countries with the highest share of the GDP due to agriculture, 54.0%, 52.6% and 43.1%, respectively (Fig. 3), do not report data on fertilizer use. The three subsequent countries in the ranking are the CAR (42.2%), Togo (42.0%) and Ethiopia (41.9%), which are respectively a very low (506 t NPK), medium (7451 t NPK) and high (395,507 t NPK) consumer of fertilizers (Fig. 3; Fig. 4; Supplementary material S1). The GDP *per capita* for the CAR is the lowest of the world (I$ 602) so that farmers in that country cannot afford the fertilizer. Incidentally, the CAR is the country with the highest undernourishment percentage in Africa. Conversely, in Togo and Ethiopia farmers are relatively richer, with values of GDP *per capita* of I$ 1315 and I$ 1425, respectively. In Togo and Ethiopia fertilizers are generally more affordable, because the government subsidizes them. Approximately 40% of the fertilizer consumed in Sub-Saharan Africa is subsidized to some degree, although the actual efficacy of subsidy policies is still being debated (AAVV, 2016; Druilhe and Barreiro-hurlé, 2012; FAO, 2017b; Juma, 2011; Minot and Benson, 2009; Morris et al., 2007; Sheahan and Barrett, 2017).

3.1.2. Fertilizer trade

Nutrient consumption data (Supplementary Material S1) show that the absolute largest consumer of N and P_2O_5 is by far Egypt, with ~1.3 M t of N and 400,000 t of P_2O_5. The largest consumer of K_2O is Morocco with 82,000 t. In Sub-Saharan Africa the largest consumers of N are South Africa (437,325 t), Nigeria (271,875 t) and Ethiopia (266,565 t); the largest consumers of P_2O_5 are South Africa (192,678 t), Ethiopia (156,538 t) and Sudan (150,570 t); the largest consumers of K_2O are South Africa (127,571 t), Côte d'Ivoire (43,271 t) and Nigeria (41,203 t). The major consumers of combined N + P_2O_5 + K_2O are South Africa, Ethiopia and Nigeria. Overall, countries expected to experience the major population increase are shown to be countries that make the largest use of fertilizer nutrients to date (Supplementary Material S1).

The average use of nutrient per area of cropland is generally low not only at a continental scale (Fig. 2), but also at a country level (Fig. 4; Supplementary Material S1). Two exceptions are given by Egypt and Mauritius. The major crops cultivated in Egypt are cotton, wheat, maize and citrus fruits (El-Fouly and Fawzi, 1995); the major crop cultivated in Mauritius is the sugar cane (Mardamootoo et al., 2010). Specific data on the actual type of fertilizer are largely unavailable, although an overview of selected countries (Supplementary Material S2) show as the favorite materials urea ($CO(NH_2)_2$) for N, superphosphates (P_2O_5 > 35 wt%) and di-ammonium phosphate ($(NH_4)_2HPO_4$) for P, and potassium chloride (KCl) for K. However, Botswana and Morocco report a significant use of ammonium nitrate (NH_4NO_3). Morocco reports a significant use of potassium sulfate (K_2SO_4) too, perhaps an indication of the importance of chloride-sensitive citrus fruits in that agriculture.

Export and import data allow to better understand some of the key issues with respect to fertilizer use in Africa. An overview of mineral fertilizers export-to-import ratios (σ) is given for a selected pool of countries in Fig. 4. For this pool, ~1.7 M t of N were imported against ~1.9 M t exported ($\sigma = 1.1$); ~0.5 M t P_2O_5 were imported against ~2.7 M t exported ($\sigma = 5.5$); ~700,000 M t K_2O were imported against ~89,000 M t exported ($\sigma = 0.1$). Note that these values do not include exclusively extra-trade but also intra-trade, implying that extra-Africa exports may actually be lower. Counterintuitively, at a continental scale both N and P_2O_5 are being exported rather than imported. However, such exports are not synonym of fertilizer production surplus, but rather a sign of a weak actual demand. Exports generate revenues but perpetuate the cycle of Africa importing food and exporting fertilizers, with local agricultural productivity suffering from both ends. On a country base, the largest importer of N is South Africa (494,943 t), the largest importer of P_2O_5 is Ethiopia (156,538 t) and the largest importer of K_2O is South Africa (291,147 t) (Supplementary materials S1 and S3).

Taking N fertilizers as an example, the largest market is in Northern Africa with ammonia (9 M t) and urea (8.5 M t) production concentrated in Egypt (>50%), Algeria and Nigeria. Ammonium nitrate is also being produced in South Africa and Zimbabwe. Additional NH_3 capacity is likely to be added by countries in Northern and Western Africa due to availability of natural gas. One example is the Jaromoro plant in Ghana. However, to date the purchase price of fertilizer products from overseas tends to outcompete that from local production, mainly because manufacturing plants in Africa are small and inefficient. Conversely, a first sign of progress come from the fact that there is a structure in place for NPK blending operations. Nigeria has thirty blenders; Mali, Ghana and Côte d'Ivoire have several each, and both Burkina Faso and Togo have one (Mulholland, 2017). A key limitation is that blending units have remained inactive for long time with facilities largely disused. Private companies such as Notore Chemicals, Indorama and the Office Chérifien des Phosphates (OCP) are leading new investments looking to challenge Yara as the leading supplier in the region (Mulholland, 2017).

Taking phosphates as an example, resources are relatively abundant (van Straaten, 2011), but development of new mines is currently too costly (Mew, 2016). However, the business incentive is more appealing than for potassium because processing of phosphate rocks leads to high-value products such as phosphoric acid (H_3PO_4), monoammonium phosphate (MAP) and diammonium phosphate (DAP). This may be one of the drivers for the OCP Group to convert itself from a mining company of phosphate rocks to a chemical producer of phosphoric acid. DAP is produced in Northern Africa (Morocco, Tunisia and Algeria), Western Africa (Senegal, Côte d'Ivoire and Togo) and Southern Africa (South Africa, Zimbabwe and Zambia) (Hernandez and Torero, 2011; *South African Fertilizers Market Analysis Report,* 2016). However, a large portion of Senegalese and the totality of Togolese phosphate rock production is exported for manufacturing the fertilizer overseas (Mulholland, 2017). Again, the major local obstacle is the development of a proper industrial and transport infrastructure. Taking potash as an example, other than small carnallite ($KMgCl_3 \cdot 6H_2O$) mining activities in Tunisia, there are no commercially active mining sites, and the DRC is the only country where one is being considered after the Allana Potash Corporation project in Ethiopia has stalled (Pedley et al., 2016; Warren, 2016). Overall, only a small amount of potash fertilizers is used in Africa (625,284 t K_2O), and unlike N or P is entirely imported (Fig. 2; Fig. 4). Because the mining sites are located mainly in Canada, Russia and Belarus, similar situations of heavy overseas reliance occur outside of Africa too. An emblematic example is Brazil, which imports ~95% of K_2O fertilizers. In that case the potash deficit is payed off by the large agricultural surplus (Fig. 1), which was achieved through the combination of scientific research, availability of flat land and political will to establish an agricultural economy intentionally dependent on North American fertilizers (Nehring, 2016). A second example is the USA, which imports ~92% of K_2O fertilizers from Canada. In this case the potash deficit is counterbalanced by both the agricultural surplus (Fig. 1A) and the advantages of the integrated regional economy of North America, including a relatively short-distance transport from Canadian mines over a well-developed infrastructure. Indeed, lack of economic integration in Africa is seen as an additional major obstacle to agricultural development (Juma, 2011).

Potash fertilizers exemplify the need to develop an African fertilizer industry avoiding mechanisms that have succeeded for megaprojects of the past, but that are likely to fail in contemporary Africa whether financing is public or private. The two key factors that have made the Canadian potash industry successful at the global level were the local mineral deposits and the massive public investments during the 1950–60s (Ciceri et al., 2015). An additional discriminant was the inherent quality of Canadian soils for which KCl was a suitable product (Ciceri et al., 2015). Currently, most African countries cannot commit the necessary budgets for developing potash projects, due to long amortization times and/or spending allocated to other priorities, one could be food imports for example. Private corporations face similar issues because due to global overcapacity the free-on-board price of potash traded internationally is too low to incentivize capital-cost investments (US$ ~ 225 per t KCl as of March 2018). Locally, potash remains expensive due to both long-distance and inland transport rather than because of the cost of mining itself or processing of the raw material, which are actually likely to have decreased over the past thirty years (Chianu et al., 2012; Mew, 2016; Morris et al., 2007). Therefore, it is likely that in Africa the local price of potash will always be unaffordable *ceteris paribus*, because in absence of local deposits either the government or the farmers will need to pay for transportation. Given that transportation infrastructure also requires massive investments, a solution would then be to identify local deposits of alternative raw materials, with the objective to develop a local fertilizer production. In that vision, the desire to engineer large-scale distribution systems may need to be counter-balanced by the necessity to adopt a business model that operates at smaller spatial scales than conventionally thought of, serving circumscribed agricultural areas rather than entire countries.

Overall, Figs. 1 to 4 confirm that policy, trade and technical advances should be considered holistically, because moving forward requires solving two key issues: i) the currently small size of the local market of both food and fertilizer and ii) the cost of the fertilizer, which conglobates implicitly the availability of raw materials, processing costs and infrastructure. Farmer skills and awareness although critical may be addressed in a second stage of the overall process of fertilizer adoption.

Regarding the size of the market (actual demand), this is often brought forward as a key limitation, assuming it to be the main driver for investments: because the market is small, there is no apparent justification for capital funds. In Africa, demand has generally been stimulated with subsidies, with both positive and negative results (Juma, 2011; Morris et al., 2007). However, as demonstrated by the experience of the Brazilian *Cerrado*, fertilizer adoption may be the result of political will rather than end-user demand (Nehring, 2016). Similarly, tariff policies in the EU and USA suggest that demand-supply principles may not guide agricultural development. Yet another example is given by the cut-flower industry that demonstrates clearly, especially in Ethiopia (50,000 t flowers; export value €146 M) and Kenya (117,000 t flowers; export value €500 M) that both investments and infrastructures are possible even in absence of an initial local demand (Belwal and Chala, 2008; Rikken, 2011). Although the market for African flowers is largely the EU market, *i.e.* not a local market, this industry demonstrates that the right policy conditions can lead to a robust productivity in relatively brief time for a sector that requires similar technologies to horticulture. A coherent and coordinated policy such as CAAPD may aid investors to access potential markets within Africa similarly to what is happening with the development of “growth corridors” (Nijbroek and Andelman, 2016; Weng et al., 2013). Although most of such corridors focus on mineral commodities, there are examples centered on agriculture such as the *Southern Agricultural Growth Corridor of Tanzania* (SAGCT).

Regarding the cost of the fertilizer, this can be between two and six times higher in Sub-Saharan Africa than in the USA, with the fraction not related to fertilizer production (*i.e.*, transportation, port duties, storage, wholesale, *etc.*) accounting to >50% of the total (Chianu et al., 2012; Morris et al., 2007; Mulholland, 2017). In the next section we discuss some options for the development of a local approach to the manufacturing of fertilizers that could reduce logistic costs, and at the same time improve yields above expectations by focusing on local soil properties. Then, if the infrastructural issue cannot be resolved it would be worth focusing on technologies that can at least abate the 50% of the fertilizer cost due to production. Africa can take advantage

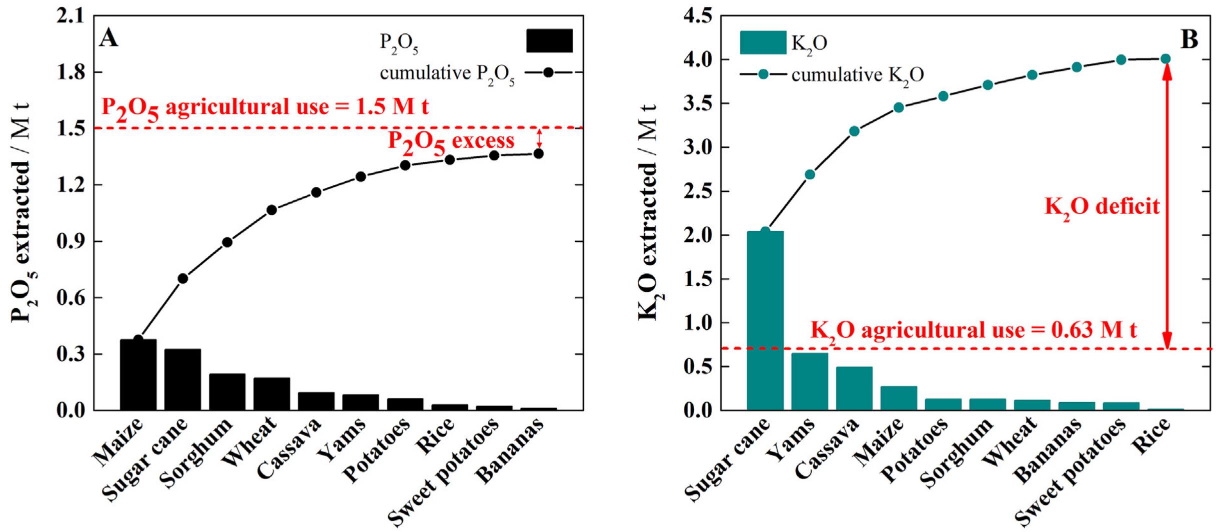

Fig. 5. Estimated (A) P_2O_5 and (B) K_2O, mined (extracted) from the soil by the ten crops with the largest annual production tonnage in Africa. In 2014, the total agricultural use of P_2O_5 in Africa was ~1.5 M t, in excess of ~86,700 t with respect to that mined by the crops shown here. The total agricultural use of K_2O was ~0.63 M t, in deficit of ~3.1 M t with respect to that mined by the crops shown here.

of the unique opportunity offered to the "late comer", implementing a comprehensive agro-ecological approach to agriculture that is now advocated for in many other areas of the world (Juma, 2011).

3.2. Overview of fertilizer research for Africa

The African context requires a fertilizer supply chain based on local materials. However, there are no known alternatives to N, P and K, which accomplish specific biological functions. These functions are inherited from the intrinsic atomic properties of such elements, for which there are no artificial equivalents.

At a global scale, N, P and K compounds originate from primary resources, and through biogeochemical and/or anthropogenic processes become redistributed in different pools of materials. Nutrient cycling investigates these redistribution processes (Ruttenberg, 2014). The primary resource is atmospheric nitrogen for N and the lithosphere for P and K. As an example, soluble P species absorbed by crops from the soil (*e.g.*, HPO_4^{2-} and PO_4^{3-}) originate from natural weathering of the mineral apatite. Therefore, crop-available P has a common origin regardless of the chosen fertilizer because it is chemical processing, whether natural such as in the case of weathering or fodder digestion, or artificial such as in the case of industrial chemical synthesis, that transfers P atoms from primary sources to fertilizer materials, for example manure or MAP/DAP products.

It is also important to acknowledge that if soil-fertility loss due to nutrient depletion from cropping (soil nutrient mining) is to be avoided (Tully et al., 2015), external inputs are inevitable to close the mass balance, because the geological rate of nutrient cycling is much slower than that necessary to feed humanity from agriculture. Accordingly, fertilizers should not be considered as unwanted exogenous chemicals, but rather as a necessity (Pradhan et al., 2014). This is well exemplified by K. In Africa, important crops for either food or cash such as sugarcane, bananas and cocoa are particularly K-demanding (Table 1; Fig. 5) (Chianu et al., 2012). In Fig. 5 it is shown that the ten most important crops for Africa in terms of annual production tonnage cause ~1.4 M t of P_2O_5 and ~4 M t of K_2O to be mined from the soil. P_2O_5 is somewhat in balance with respect to the fertilizer; K_2O is in drastic deficit (Fig. 4; Fig. 5). As a term of comparison at a global scale, the amount of P_2O_5 that originates from weathering is in the same order of magnitude as the fertilizer used in Africa (Ruttenberg, 2014), pointing again at the necessity of the fertilizer to replenish the soil with nutrients needed to meet crop demand.

This specific need of materials that bear N, P or K suggests a path for fertilizer research narrowed to technologies that can tap the value of nutrient-bearing resources. This contrasts with other global challenges such as energy supply and storage, for which researching myriad of independent technological solutions is relevant across the globe since their implementation is primarily dependent on cost-competitiveness in the market. We have anticipated in the preceding section how promoting a local fertilizer industry based on local raw materials, local soil properties and local crops would be desirable. One overarching approach that promotes that logic is given by the 4R stewardship (Bindraban et al., 2015; Johnston and Zingore, 2013; Stewart and Roberts, 2012). However, choosing the "right source" embeds an additional question, especially in Africa where standard fertilizers are either unavailable or prohibitively expensive: what are the best raw materials and processing technologies available locally? Answering that question requires determining the local nutrient-bearing pools of materials and consider the economic and chemical constraints that would favor one pool over another. Such an exercise reveals the importance of alternative materials to those traditionally used for fertilizer production, for

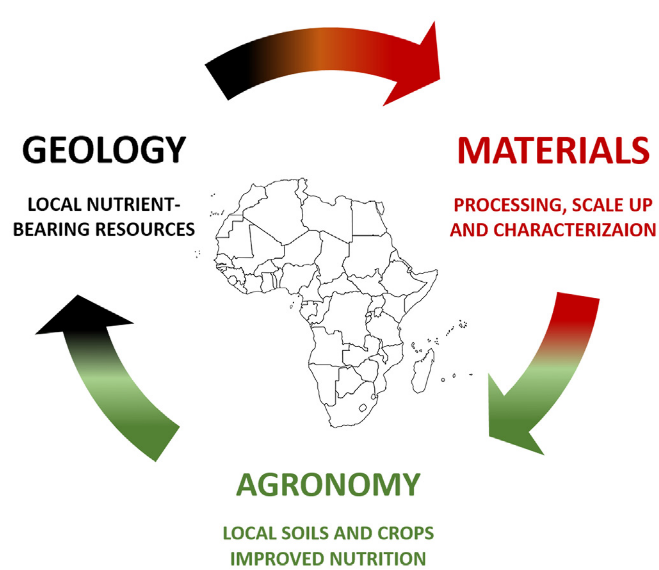

Fig. 6. Knowledge cycle to develop affordable fertilizers in Africa.

example agrominerals, primary resources often overlooked that can be processed at industrial scale and are distributed throughout the globe (Chianu et al., 2012; Ciceri et al., 2017a, 2017b; van Straaten, 2011; van Straaten, 2006). Taking into account the above considerations, this section proposes a strategy to develop fertilizer materials research in Africa. The underlying concept is depicted in Fig. 6, drawing from the idea that progress in fertilizer use can be realized only through a supply chain made independent of overseas markets (Fig. 4). At least for P and K, that chain starts with considerations on the availability of raw materials resources (geology), continues with their processing (materials science) and ends with a product ready for use in the agricultural field (agronomy). Therefore we envision geologists to lead exploration and mapping of local nutrient-bearing resources, materials scientists to lead the processing at scale into fertilizers suited to the properties of local soils, and agronomists to lead rigorous laboratory and field tests, elucidating areas of missing knowledge on soil/crop/fertilizer interactions (Bindraban et al., 2015). For Brazil, we have recently proposed a potential potassium fertilizer according to such a strategy, starting from the characterization of local K-feldspar ore (Ciceri et al., 2017a, 2017b) and processing it into a potential fertilizer (Ciceri et al., 2017a, 2017b). The research was motivated by the specific Brazilian situation, where KCl is either unavailable, unaffordable, or inefficient due to leaching in deeply weathered soils. Although detailed agronomic tests and a techno-economic analysis have not yet been provided for this alternative solution in Brazil, such an approach scales to a country level and possibly beyond when considering that the raw mineral K-feldspar is distributed throughout the globe. This approach may be particularly relevant to those African countries with similar tropical soils to those found in Brazil (Table 1).

Below we present a mini-review of three classes of materials that we deem important for their potential future role according to Fig. 6: i) agrominerals, including zeolites ii) organic fertilizers and iii) nanosized micronutrient fertilizers. We do not discuss standard fertilizers such as urea, MAP and DAP for which technological advances have been reported in the literature (Chien et al., 2009; Shaviv, 2000; Timilsena et al., 2015; van Straaten, 2007), but for whose intrinsic limitations detailed in the preceding section do not allow their widespread use in Africa. Instead we conclude indicating a direction for the future.

3.2.1. Agrominerals and zeolites

Agrominerals refer to a broad category of primary rocks and minerals that bear elements of agronomic values. The advantage over synthetic fertilizers is that they can be applied to the soil directly as powder, thus requiring minimum cost and energy for processing with respect to chemical synthesis (Ciceri et al., 2017a, 2017b; Hartmann et al., 2013; van Straaten, 2006, 2007, 2011). The key disadvantage is that their dissolution rate as measured in laboratory tests is usually orders of magnitude lower than that of soluble fertilizers, challenging their effective agronomic efficiency. There are no known N-agrominerals, other than very rare occurrences such as buddingtonite ($NH_4AlSi_3O_8$) and guano (van Straaten, 2007). For P, the most common agromineral is the primary resource itself, *i.e.* apatite, which can be used directly as a powder in the soil as a source of slow-release P. This approach also known as the *phosphate rock direct application* remains largely empirical with successful field trials under a set of given conditions (Chien et al., 2009). Phosphate rock deposits are distributed throughout Africa, offering a unique opportunity to tailor this approach for African soil (van Straaten, 2011). However, geochemical characterization of the rock deposits must be accomplished, because the rock reactivity in the field is strongly dependent on its geological origin (*e.g.*, metamorphic *vs.* igneous) and consequent chemical composition (*e.g.*, degree of fluorine and carbonate substitutions in place of phosphate) (Fig. 6). For K, several agrominerals exist, for example K-bearing silicates such as biotite and nepheline that have been discussed and tested in several contexts (Bakken et al., 1997, 2000; Ciceri et al., 2017a, 2017b; Manning, 2010, 2017; Manning et al., 2017). Particularly important is the primary mineral K-feldspar, which is one of the most abundant in the world, and throughout history has been shown to become a viable K raw material as K needs arise due to supply interruptions or price spikes of secondary sources such as soluble salts (Ciceri et al., 2015). In China, where limited supplies of K salts make the country the third largest K_2O importer (~5 M t) after the USA and Brazil (FAO, 2017c), scientists have developed routes to the production of K salts from alternative K-bearing silicates for decades (Hongwen et al., 2015; Liu et al., 2015, 2017; Ma et al., 2016). In Russia, a complementary example outside the realm of fertilizers can be found in the production of alumina (Al_2O_3) from nepheline syenite (Panov et al., 2017). Nepheline is a non-conventional resource of aluminum (Al) that is available in Russia. Incidentally, the nepheline processing produces also minor amounts of potassium carbonate fertilizer (K_2CO_3). Africa is currently in a situation of K supply bottleneck (Fig. 4 and Fig. 5), and K-feldspar seems an appropriate raw material to focus on. However, although agrominerals like feldspar may indeed be the *right source*, the issue become to understand what the *right rate* and *right time* would be, pointing at the necessity for agronomic research in that direction (Fig. 6).

Here, we include under the category of agrominerals also zeolites, which are naturally occurring hydrated aluminosilicate minerals with a wide array of applications in agriculture, catalysis, remediation and even medicine (Eroglu et al., 2017; Mumpton, 1999). The distinct feature of zeolites is their cage-like crystalline structure with cavities of approximately 2.5–7.5 Å that can exchange small molecules such as NPK nutrients or insecticides. Such molecules can be loaded in the zeolite mineral and subsequently exchanged back in a relatively controlled manner. The relatively high Cation Exchange Capacity (CEC) is of the order of 2–6 meq g^{-1} and is accompanied by the additional benefit of pH raise (Ming and Allen, 2001; Mumpton, 1999). The CEC is a function of the amount of Al that substitutes for Si in the framework structure: the greater the Al content the more the number of cations needed for charge-balance. Owing to these properties, zeolites have been used successfully as slow-release fertilizers (Eroglu et al., 2017; Ming and Allen, 2001; Mumpton, 1985, 1999; Ramesh et al., 2011). Note that the nutrient release is regulated by the intrinsic properties of the zeolitic material itself, which can be obtained simply by mining and crushing rather than by polymeric coacervation that requires costly processing (Timilsena et al., 2015). However, a global use of these potential fertilizers has not yet been implemented, with years of research that has remained confined to small trials (Ming and Allen, 2001; Mumpton, 1985, 1999). One reason is that in developed countries synthetic zeolites find a high-value commercial application as a catalyst in the cracking of crude oil (Brown, 2009). Because that application is not widespread in Africa, natural zeolites may become a platform for further fertilizer research. Estimates from the USGS indicate a global production of 2.8 M t of zeolites in 2015 (USGS, 2015), relatively low when compared with 261 M t of phosphate rocks and 39 M t of K_2O. However, large reserves of zeolites currently unexploited are likely to exist. In Africa, a known deposit of zeolite (clinoptilolite) exploited commercially is located in South Africa (Diale et al., 2011; Schoeman, 1986), but other occurrences have been reported in Botswana (Smale, 1968; Watts, 1980) as well as Kenya and Tanzania (phillipsite, erionite, analcime, and chabazite) (Hay, 1964; Mumpton, 1985; Surdam and Eugster, 1976). Other soil amendments that could improve water holding capacity such as perlite and vermiculite may also be widespread throughout Africa. One limitation is that in certain cases a source of nutrient would still be needed for loading in the zeolitic structure. Unfortunately, geological exploration for such deposits is very limited to date, and proper geochemical information is not available, suggesting an additional key area for further research in the continent (Fig. 6).

3.2.2. Organic fertilizers

Organic fertilizers include manure and crop residues, although fresh material and litter are also considered (Palm et al., 2001). Other amendments sometimes classified as organics are also worth mentioning, biochar being the key example (Duku et al., 2011; Gwenzi et al., 2015; Stevenson et al., 2014). In advanced economies, organic fertilizers are gaining increasing popularity as an alternative to traditional inorganic products, partly because of a supposed environmental and health awareness of the fertilizer and food consumer (Smith-Spangler et al., 2012; Willer et al., 2013). Given that crops do not discriminate nutrients derived from organic or inorganic sources, in the African context the distinct advantages of organic fertilizers are their local availability and reduced cost with respect to inorganic fertilizers. Some additional long-term benefits derive from their contribution to Soil Organic Matter (SOM), which promotes soil microbes and water retention in the long term, both particularly important for African agriculture (Palm et al., 2001; Sánchez, 2010). However, a key issue is that the nutrient content per volume unit of organic fertilizer is generally too low and fluctuating across time and space. This does not allow any standardization and scale up opportunity, which are still necessary to some degree even in an approach focused on local conditions (Mafongoya et al., 2006). Again, the knowledge cycle of Fig. 6 becomes relevant because primary geological sources determine the inherent quality of soils and ultimately the effectiveness of organic fertilizers. In Africa, the area dedicated to organic agriculture is only 0.1% of the total, approximately 1 M ha (Willer et al., 2013), and the policy maker has not been receptive of this approach thus far. In 2014, countries that reported the largest agricultural area certified organic were Ethiopia (160,400 ha), UR Tanzania (142,000 ha) and South Sudan (121,000 ha) (FAO, 2017c). Other sources report Uganda as the leader in organic production (228,419 ha) (Willer et al., 2013). From the perspective of nutrient mass balance, food self-sufficiency targets cannot be met through organic fertilizers (Fig. 5), which can then be hardly considered as the *right source*. However, organic crops such as coffee, olives, cocoa, oilseeds, and cotton are traded with the EU for a relatively high value and are a potential source of cash revenues. Therefore, this suggests an important future for organic fertilizers in those agricultural markets.

3.2.3. Nanosized micronutrient fertilizers

A field of very recent development is the study of the interaction between nutrient nanoparticles and crops, with the final objectives to improve yields and limit diseases (Dimkpa and Bindraban, 2016; Hong et al., 2013; Liu and Lal, 2015; Servin et al., 2015). It was shown that in some cases crops respond positively to micronutrient administered as nanoparticles, although the underlying mechanisms are yet to be elucidated (Bindraban et al., 2015; Dimkpa et al., 2017; Ramapuram et al., 2018; Servin et al., 2015; Sun et al., 2016). For example, silica is considered non-essential in bulk but has been shown to give an exceptional response in nanosized form with wheat and lupin (Sun et al., 2016). For sweet sorghum, foliar administration of zinc oxide (ZnO), calcium oxide (CaO), and magnesium oxide (MgO) nanoparticles resulted in ~16% yield enhancement in the field (Ramapuram et al., 2018). Nanoparticles of *macro*nutrients are most relevant for P–fertilizers (apatite) and lime rather than N or K that come in the form of soluble fertilizers (Liu and Lal, 2015). However, *micro*nutrients can be an important area of application of nanotechnologies because they are often administered as oxides for which extensive technical knowledge is available. Historically, micronutrients have not been a priority (Bindraban et al., 2015; Kihara et al., 2017), but are emerging as an important focus to improve the nutritional value of food (fortification) and combating so-called hidden hunger, that phenomenon by which people can intake an adequate number of calories but not adequate amount of nutrients (Dimkpa and Bindraban, 2016). In Africa, data are currently lacking on micronutrient soil deficiencies (Hengl et al., 2017; van der Waals and Laker, 2008) whereas the most common human deficiencies are iron (Fe) and zinc (Zn) (Ramakrishnan, 2002). It is known that an important connection exists between deficiencies in the soil and in humans, but thus far such a connection has not been translated in soil-tailored micronutrient fertilizers (Fig. 6) (Dimkpa and Bindraban, 2016). Micronutrients are generally sold as standalone products or formulations at fixed elemental ratios. One reason is that micronutrients are generally present in the soil, but a proper soil pH management is needed to mobilize them for crop uptake (Bindraban et al., 2015). Most micronutrients have maximum soil availability at a pH between 5.5 and 8.5. Lime ($CaCO_3$) is the most common material used to manage soil pH. However, like other standard fertilizers, lime is generally unavailable or unaffordable to most African small-holder farmers at the rate needed to manage effectively soil acidity. Agrominerals may play a role here too because mafic rocks like basalt have been proved to increase the soil pH (Gillman et al., 2001; van Straaten, 2006).

Current technology makes any large-scale implementation of nanofertilizers difficult to be envisaged in the short term. One major obstacle is the engineering effort required for manufacturing these fertilizers at scale for an affordable cost, which thus far has not succeeded even in advanced economies. An additional issue derives from possible harmful effects for the environment and human health (Hong et al., 2013). The question of the raw materials for the synthesis of nanoparticles would still need to be addressed, further to understanding the *right rate*, *right time* and *right place*. This can therefore be considered as a research frontier that Africa could take the lead on considering its direct interest for agriculture.

3.2.4. Future direction

Inevitably, when translated to the African context innovative approaches need to consider cost and opportunity for implementation by smallholder farmers, even if based on local raw materials. For example, organic fertilizers are often discussed within the broader debate on the global future of agriculture, a debate that has generated much interest in approaches that limit or even reduce rather than promote fertilizers use (Kotschi, 2013). In our view, alternative farming approaches that favor specific types of organic fertilizers over others should be encouraged, but always as a complementary rather than primary objective. A leap-frogging approach like what happened in the telecommunication sector that gave a mobile phone to millions of Africans in a relatively short time may not translate to (organic) agriculture, where intrinsic geographic realities (Table 1) and population growth that outpace the rate of technology adoption may hinder progress. Organic fertilizers require long times to build up fertility, partly because of their lower nutrient content. Existing knowledge suggests a potential longer-term future for such inputs only if multidisciplinary research will be able to identify those geographical areas and crops where their agronomic impact can be maximum (Fig. 6). Similarly, conservation agriculture, which has not been part of traditional farming in Africa is often advocated to minimize soil erosion and degradation as well as fertilizer use. However, definitive evidence of the benefits of this practice has not yet been presented for Africa calling for further and statistically validated research (Corbeels et al., 2014; Ken et al., 2009; McGuire, 2017; Muller et al., 2017; Smith-Spangler et al., 2012; Vanlauwe et al., 2014). Other approaches that focus on either legumes or agroforestry to improve Biological Nitrogen Fixation (BNF) have given promising results, but face scalability issues (Mafongoya et al., 2006). Soil-less hydroponic agriculture may face limitations too, because it relies on the quality of the nutrient solution, which again incurs in the intrinsic amount of nutrients needed by horticultural crops. Highly mechanized or robot-based agriculture faces the economic reality of the poorest countries (Fig. 3). Again, the focus to achieve maximum agronomic impact in the short-term is turned to inorganic fertilizers. In Africa however, because of learning experiences from developed and developing countries alike, agricultural growth should not occur at expenses of the environment. Fertilizers mismanagement and overuse may lead to soil, water and air pollution (Pradhan et al., 2014). In this work we suggest starting by considering nutrient-bearing resources available throughout Africa (Fig. 6) (van Straaten, 2011; Woolley, 2001), and engineer materials suitable for local soils, crops and climate. However, one anticipated issue is that no business model has been developed to date to implement knowledge from geology, materials science and agronomy in a successful commercial venture. N-fertilizers are largely dependent on the oil&gas industry, which does not rely on agricultural knowledge, and is able to produce at scale only few molecules such as ammonia and urea. Novel products are engineered by the fertilizer industry that in turn may not have detailed knowledge of the geology of the raw materials or the soil used in the final application. Its focus is mostly on formulations, *i.e.* mixing of existing molecules, and it is estimated that it invests only 0.1-0.2% of revenue in research and development (Bindraban et al., 2015). For example, the agronomic potential of alternative N-fertilizers such as urease inhibitors and coated urea has long been recognized, but no research to abate its cost has been carried out, so that they have not found a widespread global application (Christianson and Vlek, 1991). Similarly, P- and K- fertilizers are dependent on mining, a generally conservative industry with a limited perspective on innovation. As an example, the mining and processing of apatite is substantially unchanged since its invention in 1865, so that the disposal of substantial amounts of $CaSO_4$ (phosphogypsum) byproduct remains an unsolved problem to date. Another example is given by K. Although many processing technologies for the extraction of K_2O from a variety of both primary and secondary sources such as algae and biomass are known, the only industrial processes operating at scale to date are more than a century old (Ciceri et al., 2015). This situation partly derives by the quest for short-term return on industrial investments, which is unlikely to be obtained from research in mineral processing according to the strategy of Fig. 6, which requires longer timescales. Another factor is that local small-holder farmers are not the direct customers of those mining industries and a long supply chain involves too many stakeholders. Lastly, on the agronomic side much industrial research focused on improved seeds and biotechnologies, neglecting more fundamental aspects of soil chemistry and soil/crop interactions. As discussed in this work, Africa faces unique problems, and it is hoped that some of the ideas proposed in this work can propel and stimulate fertilizer research towards an innovative direction that can help to disentangle geopolitical issues from complex chemistry for the true benefit of African agriculture.

4. Conclusion

Africa is facing an unprecedented population growth that generates a genuine concern about its ability to ever become food self-sufficient. African farmers will contribute significantly to local food production by increasing in an informed manner the amount of fertilizer they are currently using. This assumes that the price of the fertilizer at the farm gate must be lowered to a level that can be afforded locally. This work has discussed the necessity of a local fertilizer approach reviewing two key aspects: fertilizer policy and trade, and potential advances of material sciences to the development of soil-tailored fertilizers for Africa. Such advances may contribute to mitigate some of the most urgent problems necessary to reduce yield gaps by the brief time left to 2030, including lowering the fertilizer cost. In the longer term, a successful implementation of the strategy outlined in this work that interconnects research in geology, material science and agronomy is hoped to result in a food self-sufficient Africa.

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Appendix A. Supplementary data

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