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Remineralizing soils? The agricultural usage of silicate rock powders: A review

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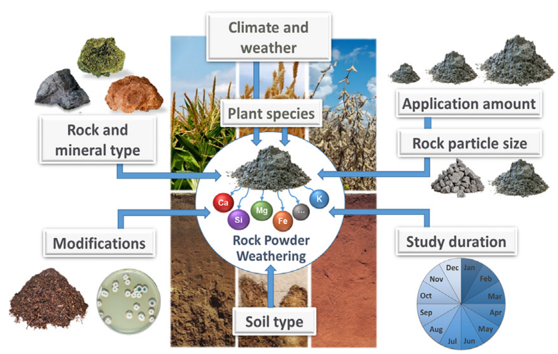
HIGHLIGHTS

- The potential of silicate rock powders (SRPs) as sustainable fertilizer is reviewed.
- SRPs can increase crop yields and improve soil health.
- The most important factors for the usage of SRPs are presented.
- Significant potential for highly weathered soils in the tropics
- SRPs can induce (a)biotic stress resistance in plants and sequester CO_2.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil nutrient depletion threatens global food security and has been seriously underestimated for potassium (K) and several micronutrients. This is particularly the case for highly weathered soils in tropical countries, where classical soluble fertilizers are often not affordable or not accessible. One way to replenish macro- and micronutrients are ground silicate rock powders (SRPs). Rock forming silicate minerals contain most nutrients essential for higher plants, yet slow and inconsistent weathering rates have restricted their use in the past. Recent findings, however, challenge past agronomic objections which insufficiently addressed the factorial complexity of the weathering process. This review therefore first presents a framework with the most relevant factors for the weathering of SRPs through which several outcomes of prior studies can be explained. A subsequent analysis of 48 crop trials reveals the potential as alternative K source and multi-nutrient soil amendment for tropical soils, whereas the benefits for temperate soils are currently inconclusive. Beneficial results prevail for mafic and ultramafic rocks like basalts and rocks containing nepheline or glauconite. Several rock modifications are highly efficient in increasing the agronomic effectiveness of SRPs. Enhanced weathering of SRPs could additionally sequester substantial amounts of CO_2 from the atmosphere and silicon (Si) supply can induce a broad spectrum of plant biotic and abiotic stress resistance. Recycling massive amounts of rock residues from domestic mining industries could furthermore resolve serious disposal challenges and improve fertilizer self-sufficiency. In conclusion, under the right circumstances, SRPs could not only advance low-cost and regional soil sustaining crop production but contribute to various sustainable development goals.

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Contents

1. Introduction

A crucial agricultural challenge is to increase or maintain yields without further degrading the Earth's environmental systems, particularly soils (Kopittke et al., 2019). Global soil degradation, of which agriculture is a major driving force, proceeds at alarming rates with about 10 million ha of cropland rendered unproductive each year (Hossain et al., 2020; Scherr, 1999). Simultaneously, additional arable land is limited, trends in crop yields decline or have reached plateaus in many countries (Brisson et al., 2010), and climate change is expected to further constrain future food production (Hari et al., 2020; Ray et al., 2019). On the other hand, agricultural intensification would result in considerable pressure on existing farmlands and requires profound advancements in soil sustaining crop production (Cakmak, 2002).

Among the major contributors to enhanced crop production are mineral nutrients, which are extracted from the soil with every harvest and must be adequately replaced by fertilizers, manures, or other amendments. In many countries however, food production currently depends on depleting large quantities of soil mineral nutrients without adequate replacement, resulting in substantial global rates of nutrient mining (Jones et al., 2013). Despite a common focus on N and P (Bouwman et al., 2017; Vitousek et al., 2009), it has been suggested that global soil nutrient depletion rates are of greatest concern for K (Sheldrick et al., 2002; Sheldrick et al., 2003; Sheldrick and Lingard, 2004; Tan et al., 2005) and that K inputs would need to at least double to replace the amounts removed from crops (Manning, 2015). Furthermore, the importance of K for plant stress resistance as well as human and animal health is increasingly emphasized (Römheld and Kirkby, 2010). Current and future K fertilization, however, faces profound challenges. Conventional K fertilizers such as KCl are often not affordable and accessible for farmers in developing countries since potash prices roughly doubled since the beginning of the century (Manning and Theodoro, 2020) and production is dominated by the Northern hemisphere (Manning, 2010). More than 80% of global potash is produced by five countries (Belarus, Canada, China, Germany and Russia), leaving many developing countries almost completely import dependent (Ciceri and Allanore, 2019; Manning, 2015). Additionally, KCl is prone towards leaching in several tropical environments due to low cation exchange capacity (CEC) (Rosolem et al., 2010; Werle et al., 2008), and losses may account for 70% of fertilizers applied in tropical sandy soils (Rosolem et al., 2018).

Besides K and other macronutrients, global nutrient mining is equally alarming for micronutrients like B, Fe, Cu and Zn (Jones et al., 2013; White and Zasoski, 1999). The extent of micronutrient deficiencies has been seriously underestimated and predominant NPK fertilization schemes have widely failed to address the fact that plants extract, to varying degrees, all 14 mineral macro- and micronutrients (Jones et al., 2013). If micronutrient deficiencies are not adequately addressed, yield responses to NPK can become very small or zero, depending on the soil type (Cakmak, 2002).

The situation is particularly severe in the tropics, the center of global food insecurity and future population growth (FAO, 2017), where more than 40% of the soils are nutrient depleted oxisols and ultisols (Sanchez, 2019). Soil nutrient depletion is the biophysical root cause for low average yields in the tropics (Sanchez, 2015), and nutrient management will be decisive to close yield gaps (Mueller et al., 2012). However, managing tropical soils is challenging since soluble NPK fertilizers are often not affordable or accessible (van Straaten, 2006), and do not replenish micronutrient deficiencies. Therefore, finding sustainable ways to manage tropical soils is of crucial importance.

One way to improve plant growth and simultaneously ameliorate soils is the usage of ground rocks. Amending soils with ground rocks is an ancient practice and their use is commonplace in agriculture, like e.g. carbonate (limestone) and sulphate rocks (gypsum) for liming and phosphate rocks (apatite) as P fertilizers (van Straaten, 2007). There is however less knowledge about the usage of silicate rocks. Rock forming silicates are by far the most abundant mineral class on Earth and contain, to varying degrees and excluding N, all mineral elements essential for plant growth (Deer et al., 2013). The release of elements through silicate weathering is one of the fundamental geochemical processes shaping the environment of the planet, and the primordial source of mineral nutrients in the soil (Schlesinger and Bernhardt, 2013). Finely ground silicate rock powders (SRPs)[1] - also called rock dust, stone meal, agrominerals or remineralizers - have therefore been proposed as slow-release fertilizers and soil amendment (Fyfe et al., 2006; Leonardos et al., 1987; van Straaten, 2007).

However, although pioneering work with SRPS has already shown several benefits in the 1930s (Albert, 1938; Hilf, 1938), research on rock powders is still limited, dispersed and partly contradictory, with results ranging from significant yield and soil improvements up to no benefits at all (Harley and Gilkes, 2000; van Straaten, 2007). The contradictions are related to the complexity of the central process, rock weathering, which is dependent upon several factors like rock type, soil type and plant species. Methodological inconsistencies and a virtual uniqueness of each trial further complicate structured approaches (Manning, 2010). For example, so far almost no study determines or controls for the soil mineralogy, although this is known to be a crucial factor influencing the effectiveness of rock powder applications (Manning and Theodoro, 2020).

In recent years however, SRPs have received renewed interest from various directions. In the Anglo-Dutch literature, research has focused on the concept of “enhanced weathering”, which aims to sequester CO_2 via silicate rock powder weathering (Beerling et al., 2018; Hartmann et al., 2013). In the tropical context, beneficial results accumulate, especially in Brazil, which is currently the epicenter of research and where the ‘Rochagem’ movement has led to an institutionalization of using rock powders in agriculture (Manning and Theodoro, 2020). Organic agriculture has a longstanding use of rock powders and its expansion increases the demand of suitable soil amendments that meet the organic growers' criteria (Abbott and Manning, 2015). Moreover, rock powders arise in massive amounts as waste products from the global mining industry, and their agricultural usage could help to resolve serious challenges regarding their management (Bian et al., 2012). There are thus pressures and potentials of global magnitude that justify a comprehensive assessment of SRPs.

SRPs have been reviewed from different perspectives: van Straaten (2002, 2007) laid out foundational work for ‘agrogeology’, Manning (2010) reviewed 20 SRP studies in terms of K nutrition, Zhang et al. (2018) outlined the historical background and recent geochemical developments in weathering studies, Manning and Theodoro (2020) report about the use of SRPs with a focus on Brazil, whereas Ramos et al. (2021) recently focused on adsorption of contaminants and enhanced weathering. What is still missing, however, is a review that provides a structured overview of the heterogeneous literature and summarizes the most important factors for practically approaching SRP usage as a basis for future research.

The purpose of this review is therefore to first present an operational framework including the most important factors for the weathering and thus effectiveness of SRPs. Then, based on the work of Manning (2010), an overview of crop trials with SRPs is presented, summarizing the most important factors and major findings of each study, to answer the question: how and under which circumstances can SRPs improve yield and ameliorate soils? Then, potential co-benefits, agronomic and environmental aspects are discussed. Finally, we aim to identify the most pertinent knowledge gaps and recommendations for future research.

[1] Silicate rock powders (SRPs) will be used as term for rocks containing only or mostly silicate minerals, since some rocks like basalt can typically contain trace amounts of oxide minerals or phosphate minerals.

2. Relevant factors for the usage of silicate rock powders

The weathering and thus efficiency of SRPs depends on a complex interplay of several factors (Fig. 1). Relevant factors include soil type, plant species, and rock/mineral type, rock particle size, application amount, study duration and modifications e.g. with compost or silicate dissolving bacteria (Bamberg et al., 2017; Harley and Gilkes, 2000; Manning, 2010; van Straaten, 2006). The majority of prior SRP trials insufficiently addressed the complexity of factors involved, which is mirrored in inconsistent study designs and lacking report of the relevant factors (Manning, 2010). Furthermore, many insignificant results with SRPs may have been caused by a poor selection of appropriate rocks and environmental conditions (van Straaten, 2007). Below, we discuss the individual factors influencing SRP weathering along with their interconnections.

2.1. Rock and mineral type

Silicate minerals have diverse structures and elemental compositions and thus exhibit diverse weathering characteristics and dissolution rates. Table 1 provides dissolution rates for major silicates and most of the minerals that were investigated in the crop trials reviewed in chapter 3. The mineral formulations in Table 1 represent the main structural elements, although many silicate minerals can contain trace amounts of several macro- and micronutrients (see Harley and Gilkes (2000) for a detailed list of plant nutrient distributions in major rock forming minerals). Generally, dissolution rates of felsic rock (e.g. granite) forming minerals such as K-/Na-rich feldspars, muscovite and biotite mica are lower compared to mafic rock (e.g. basalt) forming minerals such as Ca-feldspar, amphibole, pyroxene and olivine (Deer et al., 2013). The feldspathoids are structurally similar to feldspars but have lower Si and K contents, yet higher weathering rates.

For example, K-feldspar typically contains 3–4 times more K than nepheline but dissolves several orders of magnitude more slowly (Table 1). This implies that for a given rock not only the overall content of an element of interest must be considered, but especially the dissolution rates of its constituent minerals (Manning, 2018).

Dissolution rates (Table 1) are mostly obtained under laboratory conditions and are typically several orders of magnitude higher than those observed under natural conditions (White and Brantley, 1995). In laboratories, key dissolution parameters like pH, temperature and water flux remain constant, whereas in the soil environment they are dynamic and may exhibit interdependent and attenuated effects. Additionally, the reactive surface of a mineral might gradually change due to encapsulation in secondary mineral precipitation or cation depleted/silica rich surface areas that act as protective layer, limiting the dissolution rate. Natural weathering rates have therefore repeatedly shown inverse dependence on time, i.e. getting slower over time (Maher, 2010; White and Brantley, 2003).

Recent evaluations, however, report dissolution rates that challenge hitherto assumed slow in-field weathering rates. Two weathering stages can be differentiated, the first is the exchange of surface K^+ with H_3O^+ from soil solution, and the second is the proton catalysed hydrolysis of the Si—O and Al—O bonds in the framework structure. Ciceri and Allanore (2015) focused on first stage weathering processes, about which little is known, and found significantly higher dissolution rates for feldspars compared to second stage weathering rates.

These results are in agreement with field observations of feldspar grains that weathered several orders of magnitude faster than theoretical rates would suggest, likely due to plant and soil microbiological processes (Manning, 2018).

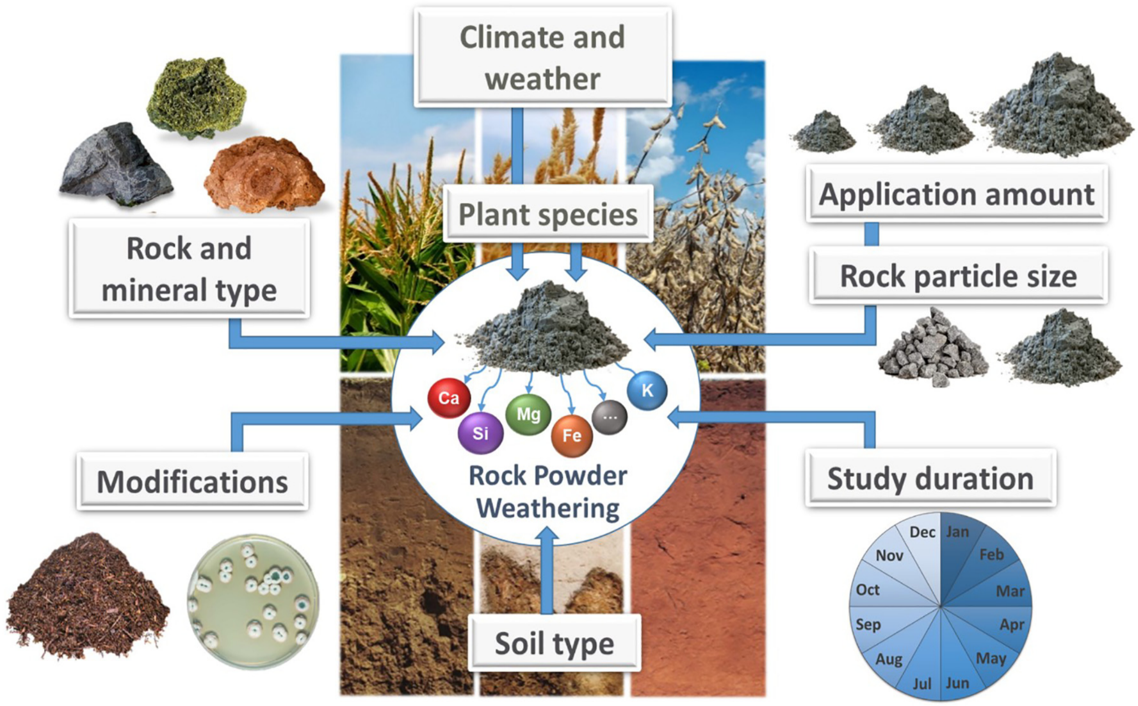

Fig. 1. Framework for the usage of silicate rock powders including the most relevant factors influencing the weathering of the rock powders. Interactions between factors are not depicted.

Besides laboratory and field rate discrepancies, compiling predictive dissolution rates for SRPs is challenging since rocks are typically composed of more than one mineral, so bulk dissolution rates need to consider all minerals, their intergrowth within the rock and textural relationship (Manning and Theodoro, 2020).

Another major challenge is that in many studies the rock names are incorrect, and experiments are thus difficult to repeat. Many studies are led by crop scientists who are often not aware of the rigour and intricacies involved in naming rocks (Glazner et al., 2019). Quarry owners rarely use the correct rock name and instead use names representing the habitual usage in their construction markets. Therefore, in studies on SRPs, correct terminology needs to be observed to improve reproducibility and consistency; igneous rocks should be named in reference to Le Maitre et al. (2002), metamorphic rocks according to Fettes and Desmons (2011) and sedimentary rocks in line with Boggs (2009).

2.2. Rock particle size

The rock particle size influences weathering rates since it relates to the reactive surface area, which increases with decreasing particle size. Several trials have shown that decreasing particle size increased the solubility of e.g. alkali feldspars (Holdren and Speyer, 1985), gneiss (Wang et al., 2000), basalt (Gillman et al., 2001) and alkaline volcanic rocks (Basak et al., 2018). Converging weathering rates were reported for several felsic rocks, with initially higher dissolution rates for particles finer

Table 1
Dissolution rate constants (25 °C, pH = 0) of silicate minerals. Relative dissolution rates show the dissolution rate of a given mineral relative to that of K-Feldspar (Dissolution rates from Palandri and Kharaka (2004)). Mineralogical data adapted from Klein and Philpotts (2017) and Manning and Theodoro (2020).

Mineral sub-group	Mineral	Formula	Dissolution rate log mol·m^{-2} s^{-1}	Relative dissolution rate
Tectosilicates				
K-Feldspar	Orthoclase	$KAlSi_3O_8$	−10.06	1
Plagioclase-Feldspar	Albite	$NaAlSi_3O_8$	−10.16	0.794
Plagioclase-Feldspar	Anorthite	$CaAl_2Si_2O_8$	−3.50	3.630.000
Feldspathoids	Nepheline	$(Na,K)AlSiO_4$	−2.73	21.400.000
Feldspathoids	Leucite	$KAlSi_2O_6$	−6.00	11.500
Phyllosilicates				
Mica	Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	−11.85	0.016
Mica	Biotite	$K(Fe,Mg)_3(AlSi_3O_{10})(OH)_2$	−9.84	1.66
Mica	Glauconite	$(K,Na)(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$	−4.80	182.000
Serpentine	Lizardite	$Mg_3Si_2O_5(OH)_4$	−5.70	22.909
Inosilicates				
Pyroxene	Wollastonite	$CaSiO_3$	−5.37	49.000
Pyroxene	Diopside	$CaMgSi_2O_6$	−6.36	5.010
Pyroxene	Enstatite	$MgSiO_3$	−9.02	11
Amphibole	Hornblende	$Ca_2(Mg,Fe)_4Al[Si_2AlO_{22}](OH)_2\ _1Ca_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$	−7.00	1.150
Amphibole	Glaucophane	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$	−5.60	28.840
Nesosilicates				
Olivine	Forsterite	Mg_2SiO_4	−6.85	1.620

than 60 μm compared to particle sizes ranging from 60 to 140 and 250–350 μm, whereas all rates became similar after 6 weeks (Niwas et al., 1987).

Mohammed et al. (2014) report that applying coarser grained biotite (10–2000 μm) resulted in significantly higher yields than fine grained (99% <63 μm) microcline and nepheline on an artificial soil (volume ration 9:1 silica sand to compost), but not on a natural soil. These results are unexpected, since biotite and microcline have similar weathering rates, whereas the weathering rates of nepheline is several orders of magnitude higher. It is assumed that the platy sheet structure of biotite compared to the 3-dimensional framework structure of microcline and nepheline could have promoted additional weathering (Mohammed et al., 2014). The relationship of weathering rate and surface area is thus a complex one and they are not necessarily proportional to each other. It is suggested that weathering does not affect the mineral surface uniformly, but to preferentially occur at highly localized sites of crystalline defects (Holdren and Speyer, 1985). Such imperfections include holes and dislocations in the mineral structure that are likely to have major effects on dissolution kinetics, specifically in the early stages of weathering. The specific surface area of a mineral is thus important for weathering, although not equivalent to the reactive surface area.

2.3. Application amounts

There is no general agreement about optimal application amounts of silicate rock powders, which is mirrored in amounts ranging from <1 t ha^{-1} ha up to >100 t ha^{-1}. Australian farmers typically apply 0.5 to 4 t ha^{-1} (Bolland and Baker, 2000), which corresponds to recommended doses of 1–3 t ha^{-1} from rock powder providers in Austria and Germany (brand “*Biolit*” and “*Eifelgold*”), and doses of 5–20 t ha^{-1} by REMIN (Scotland) Ltd. (www.reminscotland.com), although this comes without any scientific underpinning. Similarly, Theodoro and Leonardos (2006) report application amounts of up to 6 t ha^{-1} from rural small-scale farmers. Most of the trials reviewed in Section 3 applied amounts in the range of 1 to 20 t ha^{-1}. This agrees with liming rates for oxisols, which mostly span between 1 and 20 t ha^{-1}, and typically reach highest agronomic efficiency at 4–6 t ha^{-1} (Fageria and Baligar, 2008).

Very high application amounts in the range of 50–100 t ha^{-1} can lead to nutrient imbalances due to antagonistic interactions of elements, especially when rock powders primarily supply one nutrient. 100 t ha^{-1} gneiss and feldspar increased K supply but reduced the concentrations of Ca, Mg, P, Cl, Cu and Zn in dry tops of ryegrass (Priyono and Gilkes, 2008), which was also observed for equally high K amounts supplied via K_2SO_4.

2.4. Soil type

Silicate rock powders (SRP) are mostly proposed for highly weathered soils prevalent in the humid and sub-humid tropics, such as oxisols and ultisols (Leonardos et al., 1987; van Straaten, 2006). These soils differ from many soils found in temperate zones particularly in and due to their mineralogy. The reserve of weatherable minerals is large in temperate (90%) and boreal (92%) soils, whereas about 37% of tropical soils have less than 10% reserves of weatherable minerals (Sanchez, 2019). In oxisols and ultisols, most of the primary silicate minerals have weathered to oxy-hydroxide minerals and 1:1 clays, thereby reducing CEC, pH and natural geogenic nutrient supply. Artificial nutrient supply via soluble fertilizers is equally restricted due to high cation leaching rates and anion fixation particularly for P (Baligar and Bennett, 1986; Weil and Brady, 2017). In turn, the physio-chemical properties of such tropical soils suggest sufficiently high dissolution rates for SRPs to be used as alternative fertilizer and soil amendment (Bamberg et al., 2017; Harley and Gilkes, 2000; Manning and Theodoro, 2020).

It is noteworthy that Pleistocene glaciation, erosion, alluviation and volcanism remineralized (or rejuvenated) many temperate soils and thereby rendered much of their fertility, whereas many tropical soils have not been exposed to such processes in the recent geological past, and owe much of their infertility to prolonged periods of intensive weathering (Chesworth et al., 1983; Fyfe et al., 2006; Hartemink, 2002). From a pedological standpoint, remineralizing such highly weathered soils thus appears to be a plausible intervention.

For practical purposes, an important yet widely neglected issue is to consider the soil mineralogy in relation to the mineralogy of the rock applied, since dissolution occurs when there is ionic non-equilibrium between the mineral surface and the soil solution (White, 2003). Assuming that soil ionic equilibrium is roughly reached between the solution and the native minerals, adding rocks of the same mineralogy will likely not disturb the equilibrium, and weathering will thus be limited (Manning, 2018). For example, Ramezanian et al. (2013) and Ramezanian et al., (2015) tested the same rock powder with identical particle sizes and application amount for a grass/clover mixture, but the respective soils varied in their pH and mineralogy. No yield response was found when the soil and rock powder mineralogy were similar (Ramezanian et al., 2013), whereas grass yields significantly increased when the soil mineralogy overlapped less and the pH was lower (~1.0 unit) (Ramezanian et al., 2015).

Importantly, future studies must include physiochemical topsoil properties like texture, mineralogy, and pH, since common soil taxa alone are insufficient as they typically focus on agronomically less relevant pedogenic factors and subsoil properties (Sanchez, 2019).

2.5. Plant species

Mineral dissolution rates have been repeatedly underestimated by not accounting for the influence of higher plants on weathering kinetics (Bormann et al., 1998; Hinsinger et al., 2001). Plants influence the biological and physical condition of the soil particularly in the rhizosphere, where conditions can differ greatly from those in the bulk soil. Temperature, pH, moisture levels, elemental and gas concentrations fluctuate in these spheres and thereby alter the rate and quasi-equilibrium of reactions between the solid mineral phase and the soil solution (Harley and Gilkes, 2000; Marschner, 2002).

Several studies report not only considerable weathering increases through plants, but also significant interspecies differences. Hinsinger et al. (2001) showed that in the presence of various plants the release of Si, Ca, Mg and Na from basalt increased by a factor ranging from 1 to 5 compared to a control without plants. Additional element release was the lowest for Ca, whereas in the presence of bananas and especially maize (*Zea mays*) the Fe amounts released increased 100- to 500-fold. This agrees with the widely accepted view that graminaceous species (grasses) like maize have a distinctly efficient mechanism for Fe acquisition characterized by an enhanced synthesis and release of strong Fe chelatants called phytosiderophores (Römheld and Marschner, 1990). Consistent with this, several silicate rock powder studies confirm a favourable and superior response of maize compared to Italian ryegrass (*Lolium multiflorum*), perennial rygrass (*Lolium perenne*) and pak-choi (*Brassica campestris* ssp. *chinensis*) (Wang et al., 2000), eucalyptus (*Eucaliptus urograndis*) (Santos et al., 2016), holy basil (*Ocimum tenuiflorum*) (Basak et al., 2018) and black oat (*Avena strigosa*) (Ramos et al., 2019). Interestingly however, Akter and Akagi (2005) and Haque et al. (2019) report even higher weathering rates for soybean (*Glycine* max) than for maize, which was linked to the additional H^+ release during N fixation of legume associated rhizobia.

The influence of roots on weathering is furthermore related to their morphology and symbiosis with arbuscular mycorrhizal fungi (AMF). Wang et al. (2000) relates the larger and denser root systems of maize and perennial ryegrass, to their higher K acquisition from gneiss compared to pak-choi and alfalfa (*Medicago sativa*), whose roots were less entangled and in less direct contact with the rock particles. The presence of AMF has been shown to additionally increase weathering of scots pine (*Pinus sylvestris*) seedlings (Wallander and Wickman, 1999) and of buffalo grass (*Bouteloua dactyloides*) (Burghelea et al., 2018), and was recently reviewed by Verbruggen et al. (2021).

2.6. Climate and weather

The two major climatic factors influencing rock weathering are precipitation and temperature. Warm temperatures tend to accelerate weathering rates of minerals due to increases in activation energy (Kump et al., 2000). Ample laboratory work by Lasaga et al. (1994) and field studies by White et al. (1999) confirmed the temperature dependence of mineral dissolution, which is consistent with high weathering rates in several tropical climates (Sanchez, 2019). Precipitation in turn is crucial since water is central to all forms of chemical weathering in the soil (Weil and Brady, 2017) and because a high water flux promotes a soil solution that is in ionic disequilibrium with the mineral surface, thereby promoting weathering. Using SRP is therefore particularly suitable for climatic conditions prevalent in the humid and sub-humid tropics. Importantly, trials often last only several months so that fluctuating weather conditions within a given climate may contribute to the differences of SRP trial outcomes, as discussed in the next section.

2.7. Duration

Compared to water soluble fertilizer salts, SRPs are relatively slow-release fertilizers and soil amendments with potential medium- to long-term effects. Evidence for long-term ameliorations with rock powders can be drawn from forest trials, typically ranging from several years up to several decades. Single applications of fast-weathering wollastonite (3.4 t ha^{-1}) and dolomitic limestone (22.4 t ha^{-1}) improved soil pH and exchangeable base cations in several acidic forest soils for up to 15 (Taylor et al., 2021) and 21 years (Long et al., 2015), respectively. Similarly, a single application of rather slow-weathering biotite mixed with apatite ameliorated a spodosol for up to 10 years, although incipient effects on soil pH only started after 2 years (Aarnio et al., 2003), showing that potential SRP effects can be delayed. Delayed effects also occurred for phonolite rock powder applied to various K-depleted forest soils, where base cation supply only started to increase after the first year (Wilpert and Lukes, 2003). The time dimension is relevant since the duration of agronomic trials with SRPs typically ranges from several months up to two years, which might not adequately capture medium- to long-term soil changes. Some authors report beneficial effects for several years (Bakken et al., 2000; Theodoro and Leonardos, 2006), whereas others showed attenuated effects after the first year (Ramezanian et al., 2015) or after the second growing cycle (Barak et al., 1983), which was related to a fresh surface effect and other hitherto little understood effects. Overall, several authors agree that more long-term field experiments are needed to assess the full extent of potential effects (Leonardos et al., 2000; Manning, 2010; Winiwarter and Blum, 2008).

2.8. Modifications

The low dissolution rate of many silicate rocks is a major obstacle of SRPs that could be overcome by physical, chemical, or biological modifications. Physical modifications include several high-energy milling methods to decrease the particle size and the structural disordering of minerals, both of which have shown to improve dissolution kinetics considerably (Harley, 2002; Kleiv and Thornhill, 2007). Ten minutes of high-energy milling produced a feldspar powder that had dissolution rates similar to K2SO4 (Priyono and Gilkes, 2008). Priyono and Gilkes (2004) found significantly increased weathering rates for high-energy milled basalt, dolerite, gneiss and K-feldspar incubated in various soils for 10 months. However, none of the studies provides a life cycle analysis (LCA) or a cost-benefit evaluation regarding the additional energetic requirements for high-energy milling.

Physio-chemical modifications involve the fusion of K-rich silicate minerals with alkali materials ($Ca(OH)_2$ or NaOH) under hydrothermal conditions (Ciceri et al., 2017; Liu et al., 2015; Mbissik et al., 2021). The initial mineralogy is thereby significantly altered, resulting in substantially higher weathering rates and a multi-phase mineral structure that can additionally ameliorate soil physio-chemical conditions (Liu et al., 2017).

Chemical modifications include mostly acid treatments that aim to corrode the mineral structure and thereby increase nutrient release. Successful examples involve acidification of phlogopite (Weerasuriya et al., 1993) and glauconite micas (Santos et al., 2015) with nitric acid (HNO_3), hydrochloric acid (HC1) and sulfuric acid (H_2SO_4), whereas H_2SO_4 was the strongest dissolvent in both cases.

Biological modifications have been most extensively researched and involve mixing rock powders with silicate dissolving microorganisms (SDM) or organic materials like compost and manure. Several trials have shown that silicate dissolving bacteria and to a lesser extent silicate dissolving fungi are capable to substantially enhance the nutrient release from minerals (see the reviews by Basak et al. (2017), Meena et al. (2016) and Ribeiro et al. (2020)). Since SRPs contain several essential mineral nutrients except N, a rock powder enriched compost or manure could theoretically supply all needed macro- and micronutrients (Leonardos et al., 2000). Contrasting evidence exists whether the composting process itself could already increase rock weathering via microbiologically produced organic acids, raised temperatures and enhanced CO_2 concentrations (Garcia-Gomez et al., 2002; Li et al., 2020; Tavares et al., 2018). The limited evidence, however, is not directly comparable since various composting substrates were tested and differing analytical methods employed.

3. Crop trials with silicate rock powders

This section reviews 48 crop trials using silicate rock powders (Table 2). Searching the platforms Web of Science, ScienceDirect and Google Scholar for “rock powder” or “rock dust” only yields a limited number of papers, since most of the titles and keywords only include the respective rock/mineral type. The literature research was therefore mostly conducted by screening references of papers. Exclusion criteria were leaching studies without crops or trials with phosphate rocks.

The subsequent sections review the trials according to the rock/mineral class used, although several trials used various rocks, in which case the study was allocated to the most effective rock/mineral type. Application amounts are reported in different ways (e.g. kg K per ha^{-1}, g K per kg^{-1} soil or tons rock powder per ha^{-1}) and were converted into tons of SRP per ha^{-1}, since this is the most common and practically relevant unit. Information on soil properties was inconsistently reported, encompassing either soil types of various taxonomies or only specific topsoil properties.

3.1. Trials with feldspars

Several trials with feldspars have been conducted in Egypt, where conventional K fertilizers such as K_2SO_4 and KCl are oftentimes unaffordable for farmers (Ali and Taalab, 2008; Hellal et al., 2013). Moreover, KCl can be inefficient and even problematic in arid and semi-arid regions due to salinization of soils, concomitant plant chloride toxicity and inhibition of soil nitrification, among other issues (Khan et al., 2014; Vieira Megda et al., 2014). In a trial with two okra cultivars as test crops, feldspar was compared with phosphate rock, compost and NPK (Abdel–Mouty and El-Gready, 2008). All treatments increased the yields of both cultivars, and the best results were obtained with compost or phosphate rock, although feldspar mixed with compost had similar and partly higher yields as NPK. Ali and Taalab (2008) found that onion (*Allium cepa*) yield increased with increasing feldspar rates and

Table 2
Review matrix of silicate rock powder studies including the most relevant features of each study. Mineral and rock abbreviations from Whitney and Evans (2010): Ep – Epidote, Kfs – K-feldspar, Bt – Biotite, Glt – Glauconite, Mc - Microcline, Ms. – muscovite, Ne – Nepheline, Phl – Phlogopite, Qz – Quartz, Znw – Zinnwaldite. Trials are orderd according to how they appear in Section 3.

Rock/mineral	Plant	Application amount (t ha^{-1})	Soil (pH)	Particle size (μm)	Duration (months)	Trial type	Main results	Source
Feldspar	Okra	1.4	Clay (7.7)	–	24	Field	Increased yield. Feldspar plus gibberellic acid similar yield as NPK.	Abdel–Mouty and El-Greadly (2008)
Feldspar	Onion	0.9–2.6	Loamy clayey sand, (7.8)	–	3.5	Field	Increasing yield with dosage, 15% less yield than K_2SO_4	Ali and Taalab (2008)
K-feldspar	Tomato	1.3–4	Sandy soil	125–250	5	Field	Kfs insignificant, Kfs + compost: increased K uptake and yield	Badr (2006)
Feldspar	Sugar beet	0.4–1.2	Calcareous clay (8.4)	<2000	2 × 7	Field	Increased yield. Kfs + compost outyielded K_2SO_4	Hellal et al. (2013)
Feldspar	Grass	1.1	Oxisol (4.2)	<150	14	Field	Insignificant for yield and K supply	Scovino and Rowell (1988)
K-feldspar	Tomato	1–8.6	Nutrient poor acidic substrate (4.6)	10–30	3	Pot	Kfs insignificant, hydrothermally altered Kfs: increased yield, pH, plant K and Ca	Ciceri et al. (2019)
Feldspar	Rice	0.6–1.2	Clayey paddy soils (5.82/5.32)		–	Pot	Improved pH, decreased bulk density and Al / Cd toxicity, improved soil porosity	Liu et al. (2017)
Kfs, Ne + Bi rich mine tailings	Ryegrass	12–23	Peat/loamy sand/silty loam	a)100% < 590 b) K-sp finer	6	Pot	Kfs insignificant, Ne + Bi: increased K uptake and yield	Bakken et al. (1997)
Kfs, Ne + Bi rich mine tailings	Meadow-grass	1–2.5	15 different grassland soils	a) < 1000 b) K-sp finer	36	Field	Kfs insignificant, Ne + Bi: increased K uptake and yield in 3rd year similar to KCl	Bakken et al. (2000)
Mc, Bt, Ne-syenite	Leek	0.6–3	Artificial soil (6.4), sand (6.1)	<100	2 ½	Pot	Bt: Increased yield and K uptake, Ne and Mc insignificant	Mohammed et al. (2014)
Phonolite	Coffee	0.9–3.7	Oxisol (pH 4.9)	–	24	Field	Increased K and Si supply. Plant growth similar to KCl	Mancuso et al. (2014)
Phonolite (+compost)	Grass	5.4 (+33)	Oxisol	–	2 ½	Field	Insignificant for yield, increased plant Si content and soil K, Si and Na	Tavares et al. (2018)
Phonolite	Spruce	10	Alfisol (3.7–4.1)	90% < 100	60	Field	Increased base saturation, reduced nitrate leaching compared to lime	Wilpert and Lukes (2003)
Greensand	Grass mixture	5.3–7.3	Acidic (4.9) soil	1) 250–600 2) 125–250	2 ½	Pot	Similar yield as KCl, particle size 1 & 2 similar effects	Franzosi et al. (2014)
Glauconite	Durum wheat	2	(6.0)	<2000	4	Field	Increased yield, soil Ca and pH, reduced soil Mg, higher smectite content	Rudmin et al. (2019)
Glauconite	Oat	2	(6.3)	<2000	3 ½	Field	Increased yield and small but statistically insignificant soil K, Ca, Mg, P, NH4	Rudmin et al. (2020)
Glauconite	Coffee	0.5–4.8	Oxisol (4.5)	–	28	Field	Both rocks increased yield, only modified Glc increased CEC, pH, K, P, Ca, Zn, Fe.	Dias et al. (2018)
Verdete rock	Eucalyptus, maize, grass	0.6–2.6	Oxisol (5.6)	<150	3, 4	Pot	Increased yield only for grass. Modified rocks similar yield and K supply as KCl	Santos et al. (2016)
K-feldspar, phlogopite	Rice	0.2–0.5	Inceptisol	<149	–	Pot	Acidulated mica 41% higher yield than KCl, feldspar insignificant	Weerasuriya et al. (1993)
a) Syenite b) Phlogopite	Leek	a) 1–400 b) 1–70	Sand with 20% mosh peat	a) 90% < 150 b) 90% < 60	2 ½	Pot	Dose-dependent positive effect for K supply and growth	Manning et al. (2017)
Muscovite	Sudan grass	0.2–2	Alfisol (6.1), (5.6)	100% < 2000	6	Pot	Increased soil available K, K uptake and yield. Additional benefits with bacteria	Basak and Biswas (2009)
Kfs, Znw, waste mica	Spring barley	2–7	Alfisol: loamy (5.8), sandy-loamy (5.1)	2–63	1 ½	Pot	Increased yield and plant K in the order Znw > waste mica >Ksp. Zn outyielded KCl in higher dose	Madaras et al. (2012)
Serpentine	Pasture herbage	1.3	Andisol (6.3)	<500	32	Field	No effect on yield, increased Mg supply	Hanly et al. (2005)
Granite	a) Wheat b) Clover	2–20	Acidic soils (>5.2)	42% > 1000 58% < 1000	a) 7 b) 1	Field/Pot	Insignificant, 20 t ha^{-1} decreased yield in field trial but not in pot trial	Bolland and Baker (2000)
Granite and Diorite	Wheat	20	Sandy soil (4.7)	45–90	2	Pot	Diorite no effect, granite increased growth and K supply	Hinsinger et al. (1996)
Granite	Clover and ryegrass	20	Sandy podzols	<2800	1 ½, 3	Pot	Increased yield and K uptake for 2 out of 3 soils.	Coroneos et al. (1996)
Granite	Grass	25, 50, 100	Loamy sand (4.6)	<50	3 ½	Pot	Increased yield and soil pH, CEC, Na, Ca, Mg, K. reduced Al saturation	Silva et al. (2013)
Gneiss	Ryegrass	30	Sandy loam (7.2) and pure sand	90% < 40.8	2	Pot	Small but statistically insignificant increase in yield, K supply but Mg supply only in sand.	Gunnarsen et al. (2019)
Gneiss, steatite (+vermicompost)	Maize	0.6–2.5 (+10–12)	Oxisol (5.0)	150–53	2 ½	pot	Yield increase and additional effects with vermicompost,	de Souza et al. (2013)
Gneiss (+vermicompost)	Maize	4 (+16)	Oxisol (6.2)	>106 < 212	2	Field	Increased plant growth and K, Ca, Mg, K + Ni, Cr, Pb uptake	de Souza et al. (2018)

(continued on next page)

Table 2 (*continued*)

Rock/mineral	Plant	Application amount (t ha^{-1})	Soil (pH)	Particle size (µm)	Duration (months)	Trial type	Main results	Source
Gneiss, steatite (+vermicompost)	Maize	6.6 (+43.4)	Oxisol (5.1)	>106 < 212	1 ½	Pot	Increased plant and earthworm growth. Gneiss Zn source, steatite heavy metal release	de Souza et al. (2019)
a) Gneiss b) Kfs	Ryegrass	a) 25–100 b) 5–20	Loamy sand (4.8) sand (5.0)	–	12	Pot	High-energy milled rocks increased yield, soil pH, plant K and Si content.	Priyono and Gilkes (2008)
Basalt/Andesit	Grass	40	Sandy loam pH 6.2	30% > 2000 70% < 2000	36	Field	No effects on yield, soil chemistry or microbiology	Campbell (2009)
Basalt, andesite	Ryegrass wheat, clover	5–50	Peat (6.8), clay (6.9), sand (6.3),	30% > 2000 70% < 2000	36	Pot	No effects on yield, nutrient composition or soil biology	Ramezanian et al. (2013)
Basalt, andesite	Ryegrass, clover	50	Sandy loam (5.4), silt loam (5.5)	30% > 2000 70% < 2000	24	Pot	Increased grass yield, but only in first year. Not significant for clover.	Ramezanian et al. (2015)
Basalt, andesite	Clover-grass mix	50	Silt loam (4.8) sandy loam (5.2)	30% > 2000 70% < 2000	12	Pot	Increased clover growth, no effect on grass	Dahlin et al. (2015)
Andesite	Eucalyptus	3.3–6.6	Ultisol	100% < 74	5	Field	K supply but insignificant plant growth, 50% SRP + 50% NPK outyielded 100% NPK	Dalmora et al. (2020)
Dacite rock	Black oat, maize	1–7.2	Oxisol (~5)	100% < 2000 57% < 300	2 × 2 ½	Pot	Increased yield, soil pH and K, P, Ca, reduced Al toxicity	Ramos et al. (2019)
Basalt	Cocoa	5–20	Oxisol (4.3)	100% < 250 53% < 50	24	Field	Increased yield and soil K, Ca, Mg, Si, Na, . Reduced Al and Mn toxicity	Anda et al. (2013)
a) Basalt b) Tuffs	Peanut	5–50	Calcareous soil (7.8)	a) 1–250 b) 100–1000	1	Pot	Increased plant Fe, reduced effect in the 2nd harvest	Barak et al. (1983)
Basalt (+manure)	a) Grass b) Maize	3.2 (+12.8)	Sandy soil (5.3)	Ø = 24	a) 5 b) 4	Field	Reduced NH3 emissions of manure, increased yield and N recovery of manure	Shah et al. (2018)
Six rock types[1]	Rice	2.5–40	Oxisol	125–1000	4	Pot	Varying effects on yield, pH, micro- and macronutrients. Ultramafic rocks best results	Silva et al. (2014)
Basalt, diabase, bentonite.	Beech, fir, spruce	4.7	Forest soils (3.8), (5.8), (2.8)	–	36	Field	Increased pH in all soils, varying effects on soil biology	Mersi et al. (1992)
Dunite	Maize	0.04–1.5	Clayey oxisol (5.2) sandy oxisol (5.4)	–	–	Pot	Increased yield, biomass, Mg and Si concentration.	(Crusciol et al. (2019)
Dunite	Soybean	0.04–1.5	Clayey oxisol (5.2) sandy oxisol (5.4)	–	–	Pot	Increased yield, soil pH, both crop and soil Si, Mg content,	Moretti et al. (2019)
Rock mix[2] (+rice straw)	Tomato	10	(5.13)	<2000	2	Pot	Increased yield, soil pH, Ca, Mg. Decreased disease resistance and soil Mn and Zn	Li and Dong (2013)
Rock mix[3] (+ compost)	Apple	10.4 (+15.6)	Sandy loam (7.5)	<2000	24	Field	Increased yield and fruit quality. Stimulated microbiology of compost and soil	Li et al. (2020)
Basalt, porphyry graywacke,	Barley, oat, rape, clover	150–600	Sandy (5.3), clay (7.6)	60% < 63	1 ½–5	Pot/field	Yield and nutrient supply mostly positive on sandy soils, mostly insignificant on clay soil	Kahnt et al. (1986)

[1] Breccia, biotite, biotite schist, ultramafic rocks, phlogopite, manganese ore.
[2] Olivine, plagioclase, quartz, K-feldspar and biotite.

was about 15% lower than for the equivalent dose of K_2SO_4, although no control treatment was included. However, no significant difference was found when using K_2SO_4 alone or in a 1:1 combination with feldspar. Insignificant effects on K supply and yields are reported by Badr (2006) for tomatoes under feldspar fertilization alone, although combining feldspar with compost significantly increased yield and K uptake compared to compost alone. Yields peaked and even outyielded K_2SO_4 when the feldspar compost was inoculated with silicate dissolving bacteria (*Bacillus cereus*). In contrast, Hellal et al. (2013) found significant effects on sugar beet (*Beta vulgaris*) growth for feldspar alone and in combination with compost. Manning et al. (2017) grew leek (*Allium ampeloprasum*) in pure quartz sand and peat in which the only potential sources of K were KCl, feldspar or phlogopite mica. A dose dependent response was shown for both rocks on K uptake and yield, whereas the highest mica dose resulted in similar growth and K uptake as KCl.

In Colombia, Scovino and Rowell (1988) applied feldspar (sanidine) to an ultic hapludox and found small yet statistically insignificant effects on growth and K-uptake for a forage mixture of the grass *Brachiaria dyctioneura* and the legume *Pueraria phaseoloides*. The lack of significant response was related to the unexpectedly high amounts of native K in the soil and thus good yields in the control plot, suggesting that K was not a serious limitation on this site. Also, little rainfall during the trial period potentially reduced weathering.

Ciceri et al. (2019) and Liu et al. (2017) report notable effects for hydrothermally altered feldspar (HAF). Ciceri et al. (2019) showed that tomato (*Lycopersicon esculentum*) fresh weight obtained with HAF was equal to or exceeded that of KCl, whereas unaltered feldspar was ineffective. KCl led to highest leaf K content, but did not ameliorate soil acidity such as the HAF did (Ciceri et al., 2019). In China, Liu et al. (2017) found that HAF significantly increased the pH and reduced Al concentration in a moderately (5.8) and strongly (5.3) acidic clayey soil. In a preliminary field trial with rice (*Oryza sativa*), the hydrothermal product effectively decreased high cadmium (Cd) concentrations in the soil, plant and grains, which was partly related to its tobermorite and carbonate content, and pH improvements.

3.2. Trials with feldspathoids

The main feldspathoid mineral tested in most studies was nepheline. Already in the 1920s, nepheline syenite has been investigated as a source of K in Norway by the father of modern geochemistry, Goldschmidt (1922). More recent Norwegian trials compared rocks and mine tailings rich in nepheline, biotite and feldspar with KCl (Bakken et al., 1997; Bakken et al., 2000). In pot trials with Italian ryegrass (*Lolium multiflorum italicum*), the highest yield and K supply was obtained for KCl and those nepheline and biotite containing rocks that were associated with carbonatites (calcite) (Bakken et al., 1997). K from feldspar was hardly available, whereas those nepheline and biotite rich rocks with little calcite content had intermediate effects. Bakken et al. (2000) tested mostly the same rocks in a 3-year trial on various grassland sites. Likewise, feldspar was ineffective and KCl outyielded the rock treatments in the first and second year, whereas in the third and last year when no K fertilizers or feldspar were supplied, residual nepheline/biotite rich carbonatites supported grass growth as much as residual KCl.

Similarly, feldspar (microcline), biotite and nepheline were compared with KCl for growing leek on an artificial soil consisting of silica sand and compost (9:1 ratio) and on an alfisol (Mohammed et al., 2014). KCl significantly increased yield on both soils, whereas biotite at 3 t ha^{-1} increased K uptake in both soils, produced similar yields to KCl on the artificial soil and had borderline significant effects on the natural soil. Feldspar and nepheline did not show significant effects on yield compared with the control, which the authors partly ascribe to the short trial period and the high K stocks in the natural soil.

Phonolite rock, a fine grained extrusive variety of nepheline syenite, was tested in various regions. A commercial phonolite rock powder (Ekosil®) containing K-feldspar, andesine and nepheline was tested for coffee (*Coffea arabica*) on a Brazilian oxisol (Mancuso et al., 2014). Similar yields were obtained for both K sources in two growing seasons, whereas equivalents of 150 kg K_2O per ha of both treatments produced more yield than equivalents of 300 kg K_2O, which the authors ascribe to excess K supply and resulting imbalances of other nutrients.

Tavares et al. (2018) tested a phonolite rock powder containing feldspar and feldspathoids, without further specifying the mineralogy. The SRP was either applied alone or in combination with compost on an oxisol with brachiaria grass (*Urochloa decumbens*) as the test crop. Phonolite powder alone insignificantly affected yield and its combination with compost did not differ significantly from the yield of compost alone. However, the rock powder enriched composts resulted in the highest K and Si levels in the grass and the residual soil.

In a 5-year forest trial with spruce trees on a K-deficient gleyic luvisol, phonolite was compared with dolomite and K_2SO_4 (Wilpert and Lukes, 2003). K_2SO_4 sufficiently increased K in spruce needles but led to antagonistic effects on Ca and Mg contents and caused short-term acidification pulses accompanied by enhanced Al concentrations exceeding critical thresholds. K_2SO_4 showed no effects in ameliorating soil pH or the base concentrations, but phonolite and dolomite increased these variables until 30 and 60 cm, respectively. Phonolite plots had less nitrate leaching than the dolomite plots and supplied more K to spruce trees, although the K levels in spruce needles remained below the deficiency threshold.

3.3. Trials with micas

Various micas were tested, of which glauconite obtained the best results, corresponding to its highest weathering rates among the mica species (Table 1). In Argentina, Franzosi et al. (2014) compared KCl and glauconite for a grass mixture grown on an acidic (pH 4.9) soil that was not further specified. KCl produced slightly higher yields in the first harvests, although glauconite had higher overall yields after five harvests.

In western Siberia, a single application of glauconite improved the yield of durum wheat (*Triticum durum*) in the first year (Rudmin et al., 2019) and of oat (*Avena sativa*) in the second year (Rudmin et al., 2020). Glauconite slightly improved soil pH, Ca, and K of the non-specified 'dark gray' soil, although none of the differences were statistically significant.

Dias et al. (2018) compared two glauconite rich rocks, of which one was pyrometallurgically altered, with KCl in a 2.5-year coffee trial. Both rocks increased yield, however only altered glauconite had similar yields as KCl and significantly improved soil pH, CEC, available P, K, Ca, Zn, whereas KCl only improved K.

In a similar trial, Santos et al. (2016) tested pure and altered (acidified and calcinated) verdete rock (glauconite and K-feldspar rich) on an oxisol in two crop experiments: (a) maize followed by grass (*Panicum maximum*) and (b) eucalyptus. Interestingly, untreated verdete was ineffective for maize and eucalyptus but achieved the highest yield and K supply for subsequent grass growth. The altered rocks and KCl equally increased K uptake in eucalyptus and maize, whereas dry matter production only increased for maize.

Acidification was also employed by Weerasuriya et al. (1993) for phlogopite mica, which increased yield by 41% compared to KCl and limestone with the lowest application rate so far reported (0.2 t ha^{-1}). Acidulated feldspar in turn was ineffective, likely because its framework structure is less susceptible to acidification than the mica sheet structure. Superior results of mica treatments compared to KCl could have been due to multi nutrient supply from the acidified rock.

In a pot trial with pure quartz sand, in which phlogopite mica and syenite (>90% K-feldspar) were the only sources of K, Manning et al. (2017) showed that leek can obtain sufficient K for growth from the rock powders. A dose-dependent positive response was found for leek, whereas the highest amount of phlogopite outyielded KCl, and the highest amount of syenite resulted in equal yields as KCl.

The most weathering resistant mineral across the studies reviewed, muscovite mica, increased various soil K pools (water soluble, exchangeable and non-exchangeable), K uptake and yield of Sudan grass (*Sorghum vulgare*) on two alfisols. Yields additionally increased by inoculating muscovite with silicate dissolving bacteria (*Bacillus mucilaginosus*) (Basak and Biswas, 2009).

Zinnwaldite, a mica mineralogically similar to biotite but containing Li, was directly mined or obtained as a waste product from a mining sludge in the Czech Republic, and tested together with feldspar as KCl alternative for spring barley on pure quartz sand and two luvisols (Madaras et al., 2012). All treatments increased the total plant biomass and K uptake in the order zinnwaldite > waste zinnwaldite > feldspar, although the waste product released critical amounts of heavy metals (Pb, As, Cr). Zinnwaldite outyielded KCl in the higher dosage although the plant K content was lower, suggesting other growth promoting factors other than K.

In New Zealand, Hanly et al. (2005) found significant Mg supply to grasses by serpentine rock, which is a hydrated magnesium silicate mineralogically similar to micas. After 29 months, yield was however not increased by the rock powder.

3.4. Trials with granites

In Western Australia, the same biotite containing granite tested on similar acidic sandy soils with low exchangeable K showed contrasting results (Bolland and Baker, 2000; Coroneos et al., 1996; Hinsinger et al., 1996). No significant effects on yield or K-uptake were found for wheat grown in the field and clover grown in the glasshouse (Bolland and Baker, 2000). For unknown reasons, 20 t ha^{-1} granite decreased wheat yields in the field trial compared to the control with no fertilizer added (Bolland and Baker, 2000).

Hinsinger et al. (1996) found that granite significantly increased K uptake and yield (10–20%) of wheat, whereas a diorite with low K content (0.3% K2O) was ineffective.

Granite treatments were tested for ryegrass (*Lolium rigidum*) and subterranean clover (*Trifolium subterraneum*), which were grown for 7 weeks, harvested, and then regrown for another 13 weeks (Coroneos et al., 1996). After 7 weeks, granite increased the K content of both species, whereas yield only increased for clover. After 13 weeks, granite resulted in higher growth and K uptake for both species in two out of three soils.

Waste granite powder was tested in Galicia (north western Spain), where more than 90% of the national granite production takes place, on an highly acidic (pH 4.6) nutrient deficient loamy sand with ryegrass as test crop (Silva et al., 2013). The rock waste contained additional amounts of Ca incorporated during prior processing. Very high application amounts (25–100 t ha^{-1}) increased yields, soil pH, CEC, available Ca, Na, Mg and K, reduced exchangeable Al and released no critical amounts of potentially toxic elements.

Several gneisses (metamorphic rocks) with similar mineralogical compositions to granites (quartz, K and Na feldspars, micas and amphiboles) were tested pure or modified. Gunnarsen et al. (2019) found that gneiss only increased ryegrass growth and root biomass when K was omitted in the growth medium.

In Brazil, de Souza et al. (2013, 2018, 2019) evaluated the effects of gneiss and steatite powder mixed with vermicompost on maize grown on several oxisols. Vermicompost was prepared with cattle manure and the red earthworm *Eisenia andrei*, to which the rock powders were mixed at 5, 12 and 20% (*w*/w). In all trials, rock amended vermicompost significantly increased yields, whereas the earthworm weight increased in the vermicompost with 20% gneiss addition (de Souza et al., 2013) and even doubled with 12% gneiss addition (de Souza et al., 2019). Gneiss vermicompost significantly increased plant and residual soil nutrient concentrations (de Souza et al., 2018). The content of heavy metals in maize shoots reached critical limits for steatite (de Souza et al., 2019) and for gneiss (de Souza et al., 2018), although national heavy metal thresholds only exist for grains and vegetables, and not for the arial parts of plants, so longer trials are needed to analyze the transport of heavy metals to grains.

High-energy milled gneiss achieved a similar agronomic effectiveness as K_2SO_4 for ryegrass grown on Plinthic Eutrudox and a Dystric Xeropsamment, whereas milled feldspar was less effective (Priyono and Gilkes, 2008). However, the application rates of gneiss were 5-times higher than for feldspar and decreased the nutrient content of Ca and Mg to nominally deficient levels.

3.5. Trials with andesitic and intermediate rocks

A commercially available 'volcanic' rock powder (SEER center, Scotland) with a coarse particle size (60% > 0.6 mm) was used in four trials (Campbell, 2009; Dahlin et al., 2015; Ramezanian et al., 2013; Ramezanian et al., 2015). It had an andesitic composition with over 70% feldspars (albite, anorthite and orthoclase) and varying amounts of pyroxene and quartz. Although the rock powder was obtained from the same provider, Ramezanian et al. (2013, 2015) and Dahlin et al. (2015) report substantial (~15%) amounts of clay minerals, which would not be expected to occur as primary minerals in igneous rocks, whereas the rock powder analyzed by Campbell (2009, p.170) did not contain clay minerals but therefore more pyroxene and iron oxides.

After 3 years, neither Campbell (2009), evaluating the effects on a mixed grass pasture, nor Ramezanian et al. (2013), growing two wheat (*Triticum aestivum*) cultivars and a forage/grass mixture, found significant effects on yield, soil chemistry or microbiology (Ramezanian et al., 2013). Interestingly, Dahlin et al. (2015) found significant yield increases for red clover (*Trifolium pratense* L., cv. Nancy) but not for perennial ryegrass (*Lolium perenne* L., cv. Helmer), whereas Ramezanian et al. (2015) report opposing results for the same plant species, with increased yield for ryegrass but not for clover. The ineffective results from Campbell (2009) and Ramezanian et al. (2013) could partly be explained by an overlapping soil-rock powder mineralogy (Section 2.4), whereas the soils from Dahlin et al. (2015) and Ramezanian et al. (2015) contained more than 50% quartz and had a lower pH, thus potentially favouring weathering.

An equally coarse grained (<2.8 mm) andesite rock by-product showed no effects on *Eucalyptus saligna* Smith clones grown on a nutrient poor ultisol, although after 9 months available K in the soil was higher for the rock treatment than for NPK (Dalmora et al., 2020). However, 50% rock powder mixed with 50% NPK increased growth and residual available soil $P > 100\%$ NPK, suggesting potential benefits of simultaneous rock powder and soluble fertilization, possibly due to additional rhizosphere acidification via NH_4^+ uptake.

Another mining by-product, dacite rock, was supplied to black oats and maize (cultivar HIB ITAP 700) grown on an oxisols in Brazil (Ramos et al., 2019). The mineralogy of dacite is typically between andesitic and rhyolitic, whereas the one used for this trial was obviously hydrothermally altered, since it contained montmorillonite, saponite, and hematite. Significant improvements were reported for growth and nutrient uptake of black oat and maize growth. The highest application amount (7.2 t ha^{-1}) significantly raised soil pH and available K, P and Ca levels, whereas Al toxicity decreased.

3.6. Trials with mafic and ultramafic rocks

In Malaysia, basalt powder significantly increased cocoa plant growth and in situ soil solution concentration of Ca, Mg, K, Na and Si, while Al and Mn concentrations were effectively reduced to non-toxic levels (Anda et al., 2013). Soil pH and CEC increased with application amounts, whereas the best agronomic effectiveness was obtained by mixing basalt with rice husk compost at 5 t ha^{-1} each.

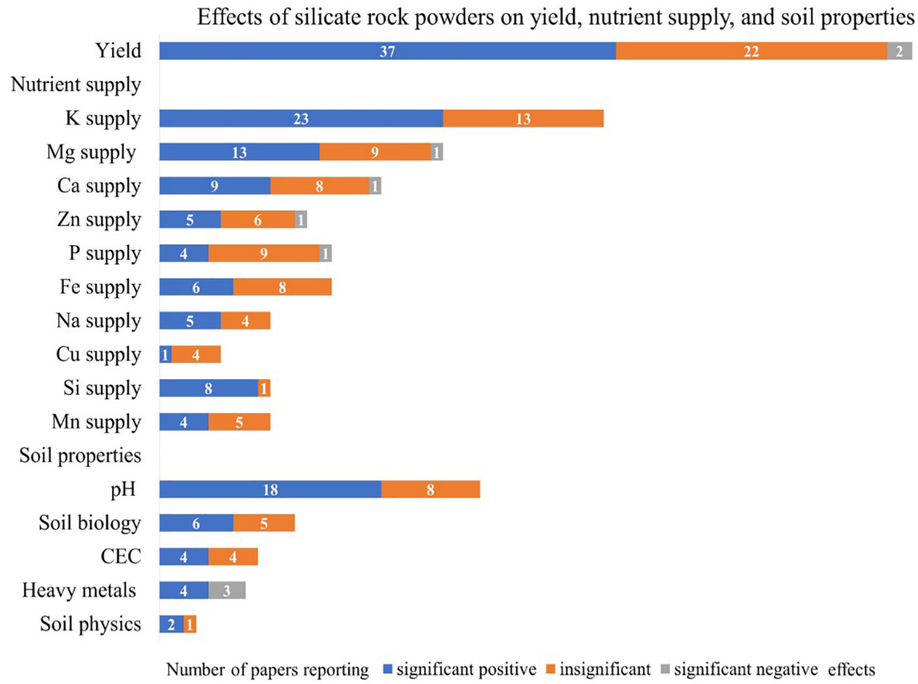

Fig. 2. Summarized effects of silicate rock powders on yield, nutrient supply, and soil properties from 40 crop trials. 'Significant positive' and 'significant negative' refers to statistically significant differences to the unfertilized control treatment in the respective study. The count for yield exceeds 40, since various studies tested more than one silicate rock powder and/or soil type and/or plant species, which were all considered individually.

Barak et al. (1983) report that ground basalt alleviated Fe-deficiency (chlorosis) of peanuts grown on a calcareous soil with equal efficiency as the commonly applied synthetic organic chelate FeEDDHA.

Shah et al. (2018) mixed '*Eifelgold*', a commercial rock powder with basaltic composition, with cattle manure, which significantly reduced the NH_3 emissions of the manure after field application. Grass and maize growth increased and the apparent nitrogen recovery (ANR) was 2–3 times higher compared to the unamended manure.

An ultramafic mining by-product substantially enhanced (up to 3-fold compared to control) rice (cv. Curinga) yield and shoot concentrations of K, Zn, Cu and Ni at non-toxic levels (Silva et al., 2014). Other mining by-products were also tested with less but mostly significant yield improvements.

Mersi et al. (1992) found significant pH increases for applying a basalt-diabase-bentonite mixture to three forest soils in Austria. Varying effects were found on soil biology, ranging from no effects for a highly acidic (pH 2.8) stagno-dystric gleysol, up to increases of nitrification, basal respiration, microbial biomass and varying enzyme activities for a calcaric regosol and cambisol, which were partly related to their higher pH (5.8).

Dunite, an ultramafic rock consisting mostly of olivine, improved plant growth and yield of maize (Crusciol et al., 2019) and soybean (Moretti et al., 2019) on a clayey and sandy oxisol in Brazil. Si and Mg levels increased for both soils and plants, in addition to beneficial effects on plant reducing sugars and foliar glucose.

In China, a rock mixture consisting of olivine, plagioclase, quartz, K-feldspar and biotite at a weight ratio 1:1:1:2:3 promoted remarkable agronomic benefits. Li and Dong (2013) report that growth, yield, chlorophyl content and photosynthetic rate significantly improved for tomatoes (cv. Shanghai 903), whereas bacterial wilt infection was reduced by 81% and 74% in the first and second year, respectively. Soil pH was raised but not CEC, and soil enzymatic activity was increased for surcease and catalase. Superior effects for all parameters were obtained by mixing the rock with rice straw. The same rock mixture was blended with a compost and thereby raised its nutrient content, metabolic activity and functional diversity (Li et al., 2020). The rock amended compost increased apple yield by 120% and 187% compared to the control in the first and second year, respectively. The fruit quality improved by means of raised superoxide dismutase, vitamin C, total sugars and hardness, and less acidity.

In a trial with basalt, porphyry, and graywacke, and the highest application amounts so far reported (150–600 t ha^{-1}), Kahnt et al. (1986) reports improved field capacity and mostly increased yields for barley, oat, rape, and clover when grown on a sandy soil, whereas the effects on the clay soil were mostly insignificant and even decreased yields when the highest amounts of porphyry, greywacke were applied.

4. Summarized effects on yield, nutrient supply and soil properties

Most of the reviewed studies in Section 3 focus on yield and K supply, although several other effects are reported, which are summarized in Fig. 2. This was done by first screening all reviewed studies from Section 3 ($n = 48$) for overall effects, and then analyzing each study according to each of the overall effects found. 8 studies did not conduct tests for statistical significance and were thus excluded, resulting in 40 studies that were considered for this analysis. An effect was counted as significantly positive or significantly negative when the SRP treatment showed a statistically significant higher or lower value than the unfertilized control, respectively. Several studies analyzed more than one rock powder and/or soil and/or plant. If this was the case, each rock, soil and/or plant type was considered individually, which is why the count for yield exceeds 40. The respective nutrient supply was evaluated by considering alterations in exchangeable and/or soil solution nutrient concentrations, and/or plant nutrient concentrations.

Two important points are: 1) The graph shows that many of the potential effects are rarely measured, thereby potentially misrepresenting the agronomic scope of SRPs, 2) Significant effects do not yet imply agronomic effectiveness, which is dependent on how much the respective factor actually increased, on the application amount and on a range of other factors that are discussed in below (see Section 6). The detailed allocation of the effects can be looked up in the Supplement Table S1, whereas in the following, some effects are shortly discussed.

4.1. Yield

As expected, most of the significant yield increases were achieved on rather acidic soils, particularly on oxisols (14 significant vs 4 insignificant), whereas results on temperate soils were mostly insignificant (5 significant vs 11 insignificant). The four insignificant results on oxisols were likely due to coarse particles sizes, low application amounts and K- feldspars/quartz rich rocks (Ramos et al., 2019; Santos et al., 2016; Scovino and Rowell, 1988; Tavares et al., 2018). In turn, the five significant results on temperate soils were achieved with highly soluble nephelines associated with carbonates (Bakken et al., 1997; Bakken et al., 2000), biotite micas (Mohammed et al., 2014) and in combination with compost (Li et al., 2020; Li and Dong, 2013). Furthermore, all trials with mafic and ultramafic rocks improved yield (Section 3.6), and almost all rock powder modifications (Section 2.8) substantially increased the agronomic effectiveness of SRP, mostly equalizing commercial fertilizers. Only in two studies, and for unknown reasons, negative yield effects are reported (Bolland and Baker, 2000; Kahnt et al., 1986).

4.2. Nutrient supply

Generally, the nutrients supplied by SRPs were above all determined by its mineralogy, and in further consequence by the trial specific factors discussed in Section 2. Potassium (K) occurs in a wide range of silicate minerals and was a primary focus of many SRP trials. Although K supply often correlated with mineral dissolution rates, unexpected benefits occurred e.g. for a range of feldspar trials in Egypt (Section 3.1), for which minor effects would be expected, given that feldspar dissolution rates are low and the soil pH was mostly alkaline. The importance of rock modification was shown by Dias et al. (2018), who tested two glauconites, but only the one pyrometallurgically altered significantly raised soil levels of K, Ca, Zn, Fe^{2+}, and, interestingly, P. The P content in the rock itself was negligible, yet the significantly higher P availability was related to the raised soil pH and to desorption of P by competing Si ions. Similar to effects on yield, the most prominent multi-nutrient supply was achieved with pure or modified mafic and ultramafic rocks applied to acidic soils. One study reports a decline of Ca, Mg, Zn, and P when very high amounts (100 t ha^{-1}) of high-energy milled gneiss and feldspar were applied, resulting from excess K supply that arguably led to an imbalance of the other nutrients (Priyono and Gilkes, 2008).

4.3. Soil pH

Several trials report increased soil pH, depicted as 'significantly positive' in Fig. 2. All authors except Bakken et al. (1997), de Souza et al. (2018), and Mersi et al. (1992) report that the increased pH was positive since the initial low soil pH constrained the respective crop growth. While many of them found rather small effects in the range of 0.2–0.4 pH units, some authors report increases of almost 2 pH units (Dias et al., 2018; Silva et al., 2013). In some cases, the pH effects were compared with lime. Mostly, the lime amendments had stronger effects on pH, although some studies suggest other benefits compared to liming, such as reduced nitrate leaching (Wilpert and Lukes, 2003), a more versatile effects on nutrient supply (Silva et al., 2013) and soil biology (Aarnio et al., 2003), and less CO_2 production when weathered (Dietzen et al., 2018).

4.4. Soil biology

Li and Dong (2013) showed that SRP raised soil sucrase and catalase enzymatic activity, and additionally alkaline phosphatase and urease when combined with compost. Mersi et al. (1992) found contrasting effects, ranging from increased nitrification, basal respiration, microbial biomass, xylanase, and protease activity on a comparably high pH regosol and cambisol, whereas no effects were measured on an acidic gleysol. The authors concluded that the SRP mixture enhanced C and N mineralization for most of the forest soils.

Li et al. (2020) found that for a rock powder amended compost the metabolic activity and microbial functional diversity increased compared to the control compost, and the community-level physiological profiling (CLPP) of the soil indicated increased microbial activity and shifts in the microbiome composition. In contrast, the CLPP analysis of the soils analyzed by Ramezanian et al. (2013) found no significant alterations after SRP incorporation. Adding gneiss to vermicompost increased the earthworm weight, although steatite had less pronounced effects (de Souza et al., 2013; de Souza et al., 2019). This agrees with Liu et al. (2011), who showed that earthworms accelerated silicate weathering, and that SRP fed earthworms had a higher bacterial diversity in their guts compared to the control. Carson et al. (2009) showed that differing minerals attract differing bacterial communities and are thus more than an inert matrix for bacterial growth. This agrees with Bennett et al. (2001) and is further emphasized through the 'mineralosphere' concept, which suggests that the mineral specific physico-chemical conditions and its inorganic nutrient supply support selective microbial colonization, similar to the rhizosphere (Uroz et al., 2015).

4.5. Heavy metals

Significant positive effects on heavy metals were related to significant reductions in toxic aluminium (Al) and manganese (Mn) levels (Anda et al., 2013; Dalmora et al., 2020; Liu et al., 2017; Silva et al., 2013), whereas significant negative findings were related to the release of heavy metals like lead (Pb) and arsenic (As) from waste mica obtained from a tungsten mining sludge (Madaras et al., 2012), and chrome (Cr) and nickel (Ni) release from steatite (de Souza et al., 2019) and gneiss (de Souza et al., 2018).

4.6. Soil physics

Although silicate rock powders directly interfere with the soil texture, only two studies measured effects on soil physical properties. Kahnt et al. (1986) showed that various SRPs increased the field capacity of a sandy soil by 12 to 23% compared to the control and that the coarse pore volume (>pF1.8) of a clay soil increased by 11% via additions of the SRPs with sandy particle sizes. However, the amounts applied were up to 600 t ha^{-1}, which are unrealistically high application amounts. Liu et al. (2017) tested low (≤1.2 t ha^{-1}) amounts of a hydrothermally altered feldspar, and report beneficial reductions of soil bulk density and an increase in porosity. Furthermore, the moisture and nutrient retaining capacity of the soil could improve via increases in 2:1 clay minerals like vermiculite, which was reported by Rudmin et al. (2019) and Mohammed et al. (2014).

5. Potential co-benefits of silicate rock powders

Despite the potential of being a multi-nutrient fertilizer and soil amendment, other co-benefits might arise from the use of SRPs. Those involve potential effects on carbon sequestration, nitrous emissions and benefits of silicon for plants.

5.1. CO_2 sequestration by enhanced weathering

The weathering of silicate minerals naturally consumes CO_2, which has regulated the global carbon cycle and thus the Earth's climate over several eons (Berner, 2004; Walker et al., 1981). For instance, the Cenozoic uplift of the Himalayas and the consequent increased weathering of silicate rocks likely resulted in a CO_2 drawdown from

Table 3
Summary of 'enhanced weathering' studies. CO_2 sequestration rates were adopted from Kelland et al. (2020).

Rock/mineral	Crop	Particle size (μm)	Application amount (t ha^{-1})	Soil (pH)	Duration (months)	CO_2 sequestered (t CO_2 ha^{-1})	Source
Olivine	Ryegrass	7–600	1.6–204	Sandy soil (4.7)	8	0.29–2.69	tenBerge et al. (2012)
Olivine	No crop	d50 = 20	a) 10 b) 50	Sandy podzol (3.4)	3	a) 3.13 b) 4.16	Dietzen et al. (2018)
Olivine	Wheat, barley	80% < 43.5/1020	220	Loamy sand (6.6)	12	0.023–0.049	Amann et al. (2020)
Wollastonite	Soybean, alfalfa	90% < 63	3–400	Sandy loam (6.6)	3.5	9.6	Haque et al. (2020)
Wollastonite	Beans, corn	90% < 25.9	125	Acidic soil (4.9)	2	39.3	Haque et al. (2019)
Basalt	Sorghum	80% < 1250	100	Clay loam (6.6)	12	2.36	Kelland et al. (2020)

the atmosphere and a cooling of the global climate (Raymo and Ruddiman, 1992). Enhanced weathering aims to accelerate this natural process by applying ground rocks on agricultural fields (Beerling et al., 2020; Hartmann et al., 2013; Seifritz, 1990).

Generally, the hydration of CO_2 (Eq. 1) forms carbonic acid (H_2CO_3) (Martin, 2017):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \quad (1)$$

Carbonic acids reacts with silicate minerals, which releases base cations (e.g. Ca^{2+}, Mg^{2}) and forms bicarbonate (HCO_3^-), and to a lesser extent carbonate (CO_3^{2-}) anions, depending on the pH (Beerling et al., 2018; Lefebvre et al., 2019). The exemplary chemical weathering for wollastonite ($CaSiO_3$) is given in Eq. (2) (Lefebvre et al., 2019):

$$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3{}^- + SiO_2 + H_2O \quad (2)$$

Following Eq. (2), CO_2 is sequestered as carbonate ions (HCO_3^-, CO_3^{2-}), most of which drains down to groundwater systems as can be seen from the Chebotarev sequence (Chebotarev, 1955a, 1955b), whereas some portion eventually reaches the oceans, where it has expected storage lifetimes exceeding 100,000 years (Renforth and Henderson, 2017). Additionally, oceans naturally become more alkaline through rock weathering and enhanced weathering of SRPs might accelerate this process, thereby ameliorating the problem of ocean acidity (Kheshgi, 1995; Renforth and Henderson, 2017).

A second and less efficient CO_2 sequestration pathway occurs when the base cations like Ca^{2+} react with carbonate anions to precipitate as secondary carbonate minerals such as $CaCO_3$ (Eq. 3), thereby permanently sequestering C in geological formations (Cerling, 1984; Jenny, 1941; Lefebvre et al., 2019). This carbonate mineral formation will herein be referred to as carbonation.

$$Ca^{2+} + 2HCO_3 \leftrightarrow CaCO_3 + CO_2 + H_2O \quad (3)$$

As outlined in Section 2.1, major gaps remain in quantifying natural weathering. These uncertainties in dissolution kinetics led to diverging extrapolations concerning the theoretical CO_2 sequestration potential of enhanced weathering (Hartmann et al., 2013; Schuiling and Krijgsman, 2006). In recent years however, some studies directly measured various elemental fluxes of SRPs. Six trials were found that conducted enhanced weathering experiments (Table 3).

All authors report increased CO_2 sequestration rates, but these differ by several orders of magnitude. These differences can be explained by differing experimental setups (rock-, plant- and soil type, rock application amounts, etc.) and differing calculation methods. Importantly, reported CO_2 sequestration rates cannot be directly transferred to most SRP trials presented in Section 3, since (i) all enhanced weathering studies used very high application amounts in the range of 50 to >100 t ha^{-1} that exceed typical application amounts (1–20 t ha^{-1}), (ii) divalent cation (e.g. Ca^{2+}, Mg^{2+}) concentrations are lower in many of the rocks investigated in chapter 3, which likely lowers potential CO_2 sequestration (Gunnarsen et al., 2019), (iii) all trials except Kelland et al. (2020) used relatively soluble silicates like wollastonite or olivine with very fine particle sizes, thereby exceeding the weathering rates of many rocks and minerals tested in Section 3. Additionally, the use of olivine might eventually be limited due to releases of the heavy metal nickel (Ni) (tenBerge et al., 2012; Amann et al., 2020). Overall, the results of Kelland et al. (2020) are particularly relevant for several reasons: (a) they used basalts, which are one of the major rocks used in SRP trials and are globally abundant; (b) the particle size was relatively coarse-grained (80% < 1.25 mm), which is similar to sieved unprocessed quarry waste (Hinsinger et al., 1996; Silva et al., 2013); (c) despite the high application rates, no critical amounts of heavy metals were released; and (d) the experiments were conducted under temperate climatic conditions, and so higher efficiency may be expected under tropical conditions.

5.2. Reduction of nitrogenous emissions

Silicate rock powders could decrease agricultural nitrous oxide (N_2O) and ammonia (NH_3) emissions, both of which considerably compromise the sustainability of agricultural systems (Kantola et al., 2017; Webb et al., 2010).

Similar to liming materials like $CaCO_3$, SRPs could reduce N_2O emissions from soils by correcting soil acidity. Even though it would be excepted that increasing soil pH will increase microbial N mineralization and thus nitrification, it has been repeatedly shown that liming decreased N_2O emissions (Borken and Brumme, 1997; Hénault et al., 2019; Samad et al., 2016). The N_2O reduction potential and preferential pH thresholds are hitherto not well understood but could be related to increased microbial production of enzymes that reduce N_2O to N_2 at neutral pH. Although basalts (approx. 20% CaO + MgO) have a lower pH buffering capacity than lime (40% CaO by weight), preliminary data of basalt applications suggest reductions of N_2O emissions (Blanc-Betes et al., 2021; DeLucia et al., 2019).

NH_3 volatilization of animal manure depends upon the concentration of NH_4^+ and NH_3 in the substrate (Ndegwa et al., 2008). Silicate minerals retrain NH_4^+ to varying degrees (Adams and Stevenson, 1964), which could theoretically decrease NH_3 emissions by reducing the concentration of free NH_4^+ ions in the substrate. Mixing 20% SRP (basaltic composition) with cattle manure significantly reduced its NH_3 emissions after field application and improved overall nitrogen recovery (Shah et al., 2012). Earlier studies with chicken manure and 10–20% SRP addition however showed contrasting effects, for which significant NH_3 reductions occurred within the first days, but thereafter increased again to eventually result in only borderline significant reductions after several weeks (Kistner-Othmer, 1989; Zaied, 1999). However, the rock powders, substrates and measurements differed, and comparisons are thus limited.

5.3. Silicon for biotic and abiotic stress resistance in plants

Despite silicon's manifold roles in plants and its tissue concentrations often equalling that of macronutrients, it is considered a beneficial rather than an essential plant nutrient (Epstein, 2009). Apart unresolved debates regarding essentiality, there is general agreement and accumulating evidence that Si induces plant biotic and abiotic stress resistance (Epstein, 1999; Guntzer et al., 2012; Haynes, 2014; Liang et al., 2015; van Bockhaven et al., 2013), mainly through two main mechanisms: Firstly, the deposition of Si as solid amorphous silica in cell walls hardens the plant skin and thereby creates a physical barrier that impedes penetration by pathogens and insects. Secondly, Si promotes the biosynthesis of considerable amounts of organic defence compounds (Epstein, 2009; Haynes, 2014). Furthermore, seven (sugarcane, rice, wheat, barley, sugar beet, soybeans and tomatoes) out of the ten most important crops (ranked by global production) are Si-accumulators (>1.0% Si on dry matter basis (Guntzer et al., 2012)), and yield increases in response to Si fertilization has been frequently demonstrated for e.g. rice and sugarcane (Korndörfer and Lepsch, 2001). These tropical crops are typically grown on highly weathered and desilicated soils with Si concentrations being usually 5–10 times less than for temperate soils. The emerging role of Si in biotic and abiotic stress resistance and the lack of Si in many tropical soils are expected to increase future demand of Si nutrition (Haynes, 2014).

The majority of positive Si supply responses, however, has been reported for highly soluble Si sources, such as calcium silicates ($CaSiO_3$), sodium silicates (Na_2SiO_3), residues of blast furnaces and straw (mainly rice straw) (Guntzer et al., 2012; Meena et al., 2014). Although typical SRP trials mostly use less soluble rocks and minerals such as feldspars, basalts and granites, Si supply was reported in most studies that measured it (Fig. 2).

In addition, some SRP trials with less soluble Si sources report improved biotic resistance. Li and Dong (2013) found that amending tomatoes with a rock powder mixture plus straw (quartz, biotite, potassium feldspar, plagioclase, olivine, and rice straw at ratios of 1:3:2:1:1:2) reduced bacterial wilt infection and improved plant health indicators like chlorophyll content and photosynthetic rate. The authors relate the increased plant resistance to raised soil pH and a higher macro and micronutrient supply, without measuring Si. Li et al. (2020) used the same rock mixture but with compost for apple trees. Plant resistance to biotic or abiotic stresses was not measured directly, but fruit hardness increased, which likely contributes to an improved physical barrier effect. Other studies (not included in Section 3) report significantly reduced bacterial rot infection and insect attack for tomatoes supplied with granite, apatite and compost, although NPK promoted higher yields (Zuba et al., 2011). Similarly, although KCl outyielded glauconite in a trial with sunflowers, the postharvest commercial durability of sunflowers was longer for plants receiving glauconite (Torqueti et al., 2016). Faraone et al. (2020) found that foliar and/or soil applications of granite dust significantly inhibited two-spotted spider mites (*Tetranychus urticae* Koch) from migrating to and/or settling on tomato leaves. Atungwu et al. (2014) found 82 to 92% reduction of root gall damage for watermelons through 2.5 to 5 t ha^{-1} crushed rock additions. The reductions are likely not due to direct Si supply, since more than 90% of the rock particles were in the sand fraction, the soil pH (6.78) was nearly neutral and the observation period was very short (60 days). The authors do not provide further information on these significant increases in biotic stress resistance.

6. Agronomic, environmental and health considerations

Apart from the factors outlined in Section 2, the agronomic effectiveness of SRPs depends upon the costs for mining, grinding, transport and spreading them on the fields, with grinding being the most energy and thus cost intensive factor (Strefler et al., 2018; van Straaten, 2006). A life cycle assessment (LCA) about the potential of basaltic rocks for enhanced weathering and soil carbonation (Section 5.1.) found transportation (related to the distance between the quarry and the place of application) as the major process negatively affecting CO_2 sequestration, whereas grinding had less effects on the CO_2 budget, which could however be related to the relative coarseness (<5 mm) of the particles. The current evidence suggests that the agronomic effectiveness is highest when SRPs are obtained as fine-grained mining residues normally low or free of charge and close to the site of application, which could simultaneously resolve a serious disposal challenge of the global mining industry.

Comparing the agronomic effectiveness with soluble fertilizers is difficult, since fertilizers typically supply readily available single nutrients apt for one growing cycle, whereas the potential effects of SRPs are manifold yet usually slower, potentially longer-term, and harder to quantify. Participatory research in Brazil showed that local SRPs were well received by small-scale farmers and single applications resulted in multiple agronomic and environmental benefits that lasted for up to five years (Theodoro and Leonardos, 2006). Furthermore, SRPs can have synergistic effects with soluble fertilizers (Dalmora et al., 2020), and should thus not be seen as substitute for them, but as an alternative and supplementary soil amendment.

Negative environmental impacts of SRPs are mostly related to critical concentrations of potentially toxic elements (PTEs) such as Ni, Pb, As, Cd and Cr. In Brazil, institutionalized frameworks for maximum limits of PTEs have been established, which is effectuated by regulatory petrographic and mineralogical analysis prior to any usage (Dalmora et al., 2020; Manning and Theodoro, 2020). This framework brought security and increased interest to both agriculturists and the mining industry, and could serve as general foundation for future SRP applications.

Proper handling and application of SRPs is important for two major reasons. First, inhaling rock dust particles during mining, grinding and application can have negative health effects (Castranova, 2000; Feigin, 1989). Second, it is practically rarely considered that surface applications might render SRPs less efficient, given that rock weathering is particularly enhanced within the rhizosphere. Thorough mixing of SRPs and soils is therefore important.

Although rocks constitute finite materials and can thus not be considered as renewable, they are among the most abundant resources on the planet and a shortage is not likely to occur at any realistic rate of application in the coming decades (van Straaten, 2002). Importantly, the amount of globally generated silicate mining waste potentially suitable for agricultural recycling is in the order of several Pg yr^{-1}, which are considerable amounts even when worldwide SRP applications are envisioned (Renforth et al., 2011). Furthermore, conventional fertilizer productions are mostly large-scale centralized industries, whereas exploitation of various locally available 'Development Minerals' could contribute to regional self-sufficiency and poverty reduction (Franks, 2020). Considering the socio-economic barriers to fertilizers in the Global South and the inertia of conventional large-scale fertilizer markets, a new paradigm of a *multilocal* rather than *global* fertilizer market can be envisioned (Ciceri et al., 2015).

7. Conclusions

We aimed to synthesise the heterogenous literature about the agricultural usage of silicate rock powders and to answer how and under which circumstances SRPs can contribute to soil sustaining crop production. Although the inherent inconsistency of SRP trials limits the degree to which they can be compared and interpreted, some major findings can be concluded: (1) SRPs must be seriously considered as soil amendment for strongly weathered soils in the humid- and subhumid tropics, since they could fill the unresolved and escalating gap for affordable and accessible K sources and micro-nutrient soil amendments, which neither conventional fertilizers nor liming can currently sufficiently address. (2) Importantly, many tropical soils are equally deficient in Si, an often overlooked non-essential nutrient for which the demand is expected to increase in the future, since 7 out of the 10 globally most produced crops are Si accumulators and ample evidence suggests that Si can induce biotic and abiotic plant stress resistance. (3) Suggested rocks are those containing fast weathering minerals like feldspathoids or glauconites, and multi-nutrient mafic—/ultramafic rocks like basalts. (4) Results on soils in temperate regions remain inconclusive and benefits will depend on a careful selection of sufficiently soluble rocks with nutrient contents that match crop demands. (5) Applications should focus on obtaining fine grained mining residues from quarries that are close to the site of application.

For future research, we suggest the following points should be considered: (i) prior consideration of the presented SRP framework to avoid a poor selection of factors, since e.g. multi-nutrient mafic rocks applied on tropical soils can still be ineffective if the particle size is too coarse; (ii) methodologically consistent and statistically rigorous trials with a minimum set of factor information, including: physiochemical topsoil properties like texture, mineralogy and pH, rock powder mineralogy, particle size and application amounts in t ha^{-1}; (iii) conducting long-term trials that assess cumulative effects and potential co-benefits over several years, and potentially decades, focusing on combining multi-nutrient rocks like basalts with Si accumulating staple crops that are capable to additionally increase weathering.; (iv) modifying SRPs to increase nutrient release shows considerable potential and must be forwarded on various fronts, such as the combination with organic materials or acidifications and hydrothermal alterations that led to K fertilizers of at least equal efficiency to that of KCl.

Eventually, if future research is addressed strategically, SRPs could not only advance self-sufficient and soil sustaining crop production but contribute to various sustainable development goals (SDGs), such as zero hunger (SDG2), sustainable consumption and production (SDG12), climate change mitigation (SDG13), and reverse land degradation (SDG 15).

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CRediT authorship contribution statement

Philipp Swoboda: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Thomas F. Döring:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. **Martin Hamer:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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

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