Arbuscular mycorrhizal fungi and potassium fertilizer as plant biostimulants and alternative research for enhancing plants adaptation to drought stress: Opportunities for enhancing drought tolerance in cocoa (Theobroma cacao L.)

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**ABSTRACT**

Drought is the most critical abiotic threat to cocoa growth and productivity. The purpose of this review is to provide an overview of the recent research and developments which have contributed to the biostimulant properties of Arbuscular Mycorrhizal Fungi (AMF) and Potassium (K) fertilizer, and suggest the best research strategies for the application of these biostimulants to enhance cocoa growth and adaptation to drought conditions. We identified multiple services provided by AMF and K fertilizers: increase nutrients uptake, activating nitrate reductase, regulating photo-synthesis and stomata conductance, improve water use efficiency, root growth etc. These multiple services could be efficiently exploited to enhance drought resilience and improve the survival rate of cocoa. Therefore, there is the need for further studies to assess the effectiveness in using either K or AMF or their combination in building the drought resilience of cocoa at the seedling phase; understand the rates of potassium fertilizers that will improve the physical (e.g. cell wall turgor, roots growth) and biochemical (e.g. Proline, polyamines, enzymatic) characteristics of cocoa seedlings to alleviate water stress. In addition, develop better K recommendations based on soil types, location specific and current cocoa varieties; understand the role of K and or AMF in enhancing drought resilience in cocoa under saline conditions and breeding cocoa genotypes with higher efficiency in K utilization and/or AMF colonization. Eventually, AMF and K can be developed as biostimulants as additional and complementary strategies to be used alongside others to improve cocoa drought resilience.

1. Introduction

West Africa (Côte d’Ivoire, Ghana, Nigeria and Cameroon) accounts for over 70% of global cocoa production (International Cocoa Organization, ICCO, 2019). Evidence show that there is an increasing demand for cocoa from West Africa by the chocolate and confectionary industry (Schroth, Läderach et al., 2016; Schrot et al., 2017; Somarriba & Lopez-Sampson, 2018). For example, Blommer (2011) predicted that a 3% growth in cocoa consumption would require the addition of 1.8 million metric tons of cocoa by 2025, and the production of cocoa crop would need to increase by nearly 50% to meet the projected demand. One major challenge however is the increasing impact of drought on cocoa production in West Africa (Armah et al., 2011; Bari et al., 2016; Hutchins et al., 2015; Lahive et al., 2019; Schroth, Läderach et al., 2016).

For instance, Läderach et al. (2013) predicted that many areas in Ghana and Côte d’Ivoire will no longer be suitable for cocoa production due to projected decline in rainfall by 2%, 11% and 19% in the years 2020, 2050 and 2080 respectively. In stressing the impact of drought on cocoa production in West Africa, Santosoa et al. (2018), Mittler (2006), and Suzuki et al. (2014) suggested that among all the environmental/abiotic stresses, drought is the most critical threat for cocoa growth and productivity. It is however important to note that the effect of drought stress depends on the developmental stage of the cocoa plant, its severity, duration of the stress and the cocoa cultivar. So, unlike mature cocoa trees which have greater access to water and soil nutrients, cocoa at the nursery stage (seedling) is more sensitive to drought and will not recover if it is stressed beyond a critical level (Lahive et al., 2019). For instance, in Ghana anecdotal estimates of in-field survival of cocoa seedlings implied that only 20% actually survive the dry spells within the first 24 months after planting. Thus, high seedling
mortality during the establishment phase of cocoa has become a critical constraint to sustainable cocoa farming.

As an antidote to such abiotic stresses, many studies have focused more on selecting cocoa hybrids with high percentage survival, cocoa genotypes showing varying degrees of intra-specific variations for early growth, genotypes that show high seedling vigour and pod production and those that show improvement in cocoa yield (Balig & Fageria, 2017; Lahive et al., 2019; Padi et al., 2013). Hence, the urgency for complementary or alternative research approach that will focus on cocoa seedling resilience and adaptation to environmental stress, such as drought, cannot be overemphasized.

The concept of biostimulants is an emerging area of interest in research, where, with reduced need for chemical fertilizers, products/organisms are used to improve the growth of plants and increase plants’ resilience to excessive water, drought and other abiotic stresses.

Potassium (K) fertilizers and native Arbuscular Mycorrhizal Fungi (AMF) could provide such additional and complementary strategies to be used alongside others currently in development. For example, K has been shown to enhance drought resistance in different annual crops under water stress conditions (Benloch-Gonzalez et al., 2008; Egilla et al., 2001; Pervez et al., 2004; Shahid, 2006; Zain Nurul & Ismail, 2016). The role of K in plants under water stress has been attributed to its ability to maintain the osmotic potential and turgor of the cells and regulate the stomatal function; attributes that enhances drought resilience in plants (Marschner, 2012; Umar, 2006). In addition, K has a protective role through the maintenance of a high pH in stroma and against the photo-oxidative damage to chloroplasts (Cakmak, 1997).

Moreover, K is involved in activating a wide range of enzyme systems which regulate photosynthesis, water use efficiency and movement, nitrogen uptake and protein building in plants (Nguyen et al., 2002). Romheld and Kirkby (2010) further indicated that appropriate potassium supply substantially increased the root growth, thereby; increasing the root surface area with corresponding increase in water uptake under water deficit conditions.

In respect of AMF, they are known to form symbioses with the roots of their host plant species in exchange for carbon (Barrows & Pfleger, 2002). The potential role of AMF to increase plant uptake of nutrients and water, improve nutrient use efficiency and produce higher biomass and yield is well recorded in literature (Davies et al., 1993; Droh et al., 2016; George et al., 1995; Grümberg & Urceley, 2015). The challenge however is identifying, isolating and inoculating the appropriate native AMF to form symbiosis with a tree crop like cocoa.

It is therefore highly probable that appropriate K nutrition and AMF isolation and inoculation could provide that complementary research approach that can focus on cocoa seedling resilience and adaptation to drought stress.

In this review, we provide an overview of the current developments which have contributed to the biostimulant properties of AMF and potassium fertilizers. In the review, we also outline and recommend the opportunities that could be efficiently exploited by applying these biostimulants to enhance resilience of cocoa seedlings to drought and other stresses that may be associated with climate change.

2. Effect of water stress (drought) on cocoa tree growth and productivity

Cocoa is highly sensitive to environmental stress. Among the abiotic stress, drought stress is one of the key constraints to the establishment and productivity of cocoa trees (Djan et al., 2018; Gateaux-Rey et al., 2018; Schroth, Laderach et al., 2016; Suzuki et al., 2014). This assertion has been confirmed in Ghana (Ameyaw et al., 2018; Hutchins et al., 2015), Nigeria (Agbongiarhuoyi et al., 2013; Trinidad and Tobago (Eitzinger et al., 2015) and Costa Rica (Deheuvels et al., 2012; Hutchins et al., 2015; Phillips, 2015), in surveys of cocoa farmers that were intended to assess the relative effects of climatic change on the productivity of cocoa. For instance, Ameyaw et al. (2018) assessment of cocoa farmers knowledge and perception of climate change impact on cocoa production in Ghana found that, out of the 205 farmers interviewed, 89% and 81 % mentioned reduction in the amount of rainfall and reduced length of the wet season as major constraints, in addition, 81% of the farmers indicated that dry spells (drought) had increased. Our understanding of what constitutes drought stress and plants strategies to confront water limitation is simplified (Figure 1) by Moradi (2016) who indicated that plants experience drought when the available water in the soil is reduced and water lost continuously by evaporation and transpiration to atmospheric conditions. Unfortunately, with the current changes in climate, the world cocoa production is negatively affected by this drought stress, with an expected production decrease by
up to 15% (Gateau-Rey et al., 2018; International Cocoa Organization, ICCO, 2019).

Of greater worry is that greater percentage of this effect will be in West Africa (e.g. Côte d’Ivoire and Ghana) where over 70% of the global cocoa is produced, provide livelihood to over 30% of the population and majority of the farmers depend on rain-fed agriculture with low adoption of irrigation technology (Lahive et al., 2019; Friedman et al., 2019; Ayegboyin & Akinrinde, 2016; Läderach et al., 2013; Schroth, Läderach, et al., 2016; Carr & Lockwood, 2011). Outside West Africa, Keil et al. (2008) found that very severe drought caused a 62% loss of cocoa production in Sulawasi-Indonesia (the third largest producer of cocoa in the world).

The mechanism with which drought stress affect cocoa growth and productivity varies, with Tee et al. (2018) and Ayegboyin and Akinrinde (2016) further suggesting that the effect depends on the developmental stage of the plant, cultivar genetics, severity and duration of drought. For instance, Zakariyya and Indradewa (2018) and Alban et al. (2016) found that under drought condition, cocoa photosynthetic rate drastically declined, and this significantly induced the reduction of vegetative growth.

Other researchers found that under drought stress, cocoa leaf area and stem diameter declined up to 20% (Ayegboyin & Akinrinde, 2016; Lahive et al., 2019), plant height declined by more than 10% (Chibuike & Daymond, 2015) and seedling growth reduced (Djan et al., 2018; Lahive et al., 2019). Physiologically, drought stress also inhibits the activity of nitrate reductase, which has the functions of protein production, regulation of photosynthesis, water use efficiency and movement, and is a regulator of nitrogen assimilation in cocoa plants (Mandi et al., 2018; Nguyen et al., 2002). For instance, the lower photosynthetic rate reflects in lower growth and yield of cocoa, this according to Zakariyya and Indradewa (2018) is caused in consecutive ways: (a) qualitative and quantitative degradation in photosynthesizing pigments, especially chlorophyll, (b) the reduction of CO₂ uptake due to stomatal closure, and (c) low water compound because water in soil and plant is limited.

In addition, stomatal conductance and chlorophyll are important in photosynthesis, however, Prihastanti (2010), Ayegboyin and Akinrinde (2016), and Ayegboyin (2012) found that cocoa grown on low soil water content had these parameters negatively affected with chlorophyll a and b pigment lower than those grown on adequate soil water content, while majority died during the “longer-than usual” dry spell.

Likewise, long periods of high temperatures above 30 °C increase the rates of soil evaporation, which increase the water stress (drought) and this affect the physiology
of the cocoa tree and reduce bean size (Daymond & Hadley, 2008; Milz & Ssebunya, 2011). Moreover, cocoa trees are known to have low light saturation point (LSP) of 400 μ E m\(^{-2}\) s\(^{-1}\) and a low maximum photosynthetic rate of 7 mg dm\(^{-1}\) h\(^{-1}\) (Anim-Kwapong & Frimpong, 2005; Asomaning et al., 1971; Milz & Ssebunya, 2011). The photosynthetic rate of cocoa declines if it is exposed to light intensities beyond 60% of full sun light (1800 μ mol m\(^{-2}\) s\(^{-1}\)), with prolonged exposure resulting in damages to the photosynthetic mechanism of the leaves due to soil water evaporation (Anim-Kwapong & Frimpong, 2005; Milz & Ssebunya, 2011; Daymond & Hadley, 2008; Asomaning et al., 1971).

It is worth noting that, cocoa and other plant species resilience to drought stress is mostly by the adjustments in their morphological parameters (stem thickness, leaf thickness, reduced leaf area etc), physiological (reduction in stomata opening, transpiration etc) and biochemical characteristics (increased nitrate reductase activity etc). Irrigation is the predictable panacea to help enhance these parameters and characteristics. However, it has not been widely adopted in West Africa, where majority of the world cocoa is produced, due to practical limitations such as the remoteness of smallholder farms from water supplies and cost restrictions (Carr & Lockwood, 2011). Therefore, there is an urgent need to find complementary or alternative solution that will improve cocoa growth (with reduced need for chemical fertilizers) and increase its resilience to water stress (drought) and other abiotic stresses under these limitations.

3. Potential role of biostimulants in mitigating drought stress in cocoa

3.1 Role of potassium (K) in plants under water stress (drought) condition

Potassium (K\(^+\)) is considered as an essential nutrient and the most abundant cation in plants. It affects most of the biochemical and physiological processes that influence plant growth and metabolism and development. K\(^+\) in plants’ cytoplasm is between 100 and 200 mM, and apoplastic K\(^+\) concentration may vary between 10 and 500 mM (Shabala & Pottoso, 2010; White & Karley, 2010). The recent increased utilization of potash fertilizers in most regions of the world has been attributed to the positive impact of K\(^+\) on crop yield (Dong et al., 2010; Pettigrew, 2008). Apart from the growth and developmental attributes, K\(^+\) and K fertilizers play critical roles in the survival of plants exposed to various biotic and abiotic stresses, especially drought stress (Gong et al., 2020; Hasanuzzaman et al., 2018; Khan et al., 2018). This is done through a number of inter-connected physiological and regulatory pathways (Figure 2). For instance, sufficient K status increased cell membrane stability, root growth, leaf area and total dry mass for plants living under drought conditions and also improved water uptake and water conservation. Maintaining an adequate K nutritional status is critical for plant osmotic adjustment and for mitigating ROS damage as induced by drought stress (Wang et al., 2013).

Umar (2006) and Marschner (2012) further indicated that potassium has the ability to maintain the osmotic potential and turgor of the cells and also regulates the stomatal functions. This remarkable function according to Zakariyya et al. (2016) is a strategy of plants for diminishing water loss through transpiration processes by regulating stomatal conductance. Furthermore, the protective role of K in plants suffering from drought stress has been attributed to its maintenance of a high pH in stroma and against the photo-oxidative damage to chloroplasts (Cakmak, 1997). This function is essential since stromal pH in the chloroplast is known to be linked to internal (i.e. stromal) and external K\(^+\). The outflow of K from the stroma is associated with a lowered stromal pH (stromal acidification), and this results in photosynthetic inhibition (Wu & Berkowitz, 1992). Thus, photosynthetic inhibition under drought condition means lower plant biomass; poor growth and this could lead to death of plant.

Potassium is also responsible in activating nitrate reductase; an enzyme critical for the production of protein in plants, regulating photosynthesis, water use efficiency, nitrogen uptake and protein building (Mandi et al., 2018; Nguyen et al., 2002). However, nitrate reductase is known to be sensitive to water stress because its metabolic pathway is regulated by water (Chachar et al., 2016; Lisar et al., 2012; Mujtaba et al., 2016; Zakariyya & Indradewa, 2018). Cakmak (2005) further provided an explanation for the increased need for K by plants suffering from drought stress. The author showed that K is required for maintenance of photosynthetic CO\(_2\) fixation since drought stress is associated with stomatal closure and thereby with decreased CO\(_2\) fixation (Figure 3).

Stocks of exchangeable K in cocoa soils varied from 100 to 560 ha\(^{-1}\), which is between 27 and 61% of total exchangeable K accumulated in the cocoa systems (Van Vliet & Giller, 2017). In Ghana, the current recommended K application rate is 67.5–75.5 kg K\(_2\)O ha\(^{-1}\) (Afrifa et al., 2009), but there is limited research and knowledge in the evaluation of the role of K in cocoa trees under drought condition. However, there are enough evidence on the drought resilient role of potassium in cassava (Ezui et al,
For example, in a study by Premachandra et al. (1991), maize plants with higher K applications showed greater adaptation to water stress, and this was attributed to the role of K in osmotic adjustment, increased root elongation.
and maintenance of cell membrane stability (Rama Rao, 1986; Romheld & Kirkby, 2010).

In addition, in an experiment to assess the effects of potassium rates and types on rice (Oryza sativa) under cyclic water stress, Zain Nurul and Ismail (2016) found that under three levels of potassium rates (80 kg K₂O ha⁻¹, 120 kg K₂O ha⁻¹, and 160 kg K₂O ha⁻¹) and two types of potassium (KCl and K₂SO₄) application, high K rates minimized the effects of drought on rice growth and physiology, increased the nutrient uptake and repaired damaged tissue under cyclic water stress.

Similarly, in a study to investigate the response of peanut crop to foliar spraying of potassium under water stress conditions, Aboelill et al. (2012) found that spraying peanut plants with potassium fertilizer gave higher growth parameters; i.e. number of branches per plant, dry matter of pods, leaf number and stem diameter in two experimental seasons. This finding was not different from the results of Aslam et al. (2013) where the application of potassium increased maize tolerance to drought stress by enhancing root growth, stem elongation, and increasing leaf water potential, osmotic potential and turgor potential. Likewise, they found K to have enhanced photosynthetic rate and the yield and yield related parameters of the maize crop. The finding of the authors seem to support the earlier findings of Lindhauer (1985) who evaluated the influence of K nutrition and drought on water relations and growth of sunflower (Helianthus annuus L.). Lindhauer’s result showed that even under water stress conditions, the up to 5 times higher K concentrations in the tissue caused an increased dry matter production and total leaf area was less reduced. Finally, preliminary study by Djan et al. (2018) found that under water stress conditions, K-treated cocoa seedlings (0, 1, 2 or 3 g/plant of muriate of potash) had increased root and shoot biomass, higher leaf water content, higher chlorophyll fluorescence and reduced electrolyte leakage from leaves leading to improved vigour. Therefore, if the current recommended K application rate (67.5–75.5 kg K₂O ha⁻¹) is increased (e.g. >80 kg K₂O ha⁻¹), it could enhance the protection capacity of K on cocoa trees.

### 3.2 Role of AMF in plants under water stress (drought) condition

Arbuscular Mycorrhizal Fungi (AMF) are obligate biotrophs that form symbioses with the roots of most plant species (Barrows & Pfieger, 2002; Giovannini et al., 2020). They obtain their carbon and lipids from their host plant and then release mineral nutrients for the benefit of their associated plant (Jiang et al., 2017; Lugnibuehl et al., 2017).

The relevance of AMF as biostimulant is anchored on its potential to increase plant nutrient uptake, improve plants resilience to drought, and reduce the use of pesticides and inorganic fertilizers (Droh et al., 2016; Finlay, 2008; Song et al., 2020). For abiotic stresses, the mechanisms of adaptation of AMF to these stresses are generally linked to increased hydromineral nutrition, ion selectivity, gene regulation, production of osmolytes, extension of the root absorbing area and the synthesis of phytohormones and antioxidants (Diagne et al., 2020). These benefits are influenced by its ability to colonize its host plant, a phenomenon which depends on the fungal genotype, the soil characteristics and plant genotype. Giovannini et al. (2020) posited that different AMF strains show optimum germination when cultivated in environments that have characteristics which are similar to those from where they were originally isolated.

The advent of climate change and its subsequent impact on cocoa saplings raise the need to explore how the role of AMF could be used as biostimulant to help in cocoa seedling establishment, adaptation and resilience to drought.

In a recent study on AMF on tree crops, Edy et al. (2019) and Famuwagun and Agele (2019) found that AMF from different origin can colonize cocoa and coffee and has the potential to improve their vegetative growth (stem diameter, plant height and leave area).

Similar results have been found by Mathur et al. (2018) and Abdel-Salam et al. (2018) on wheat (Triticum aestivum) and damask rose (Rosa damascene Mill), respectively. Both studies found that AMF could alleviate the adverse effects of drought stress and improve leaf relative water content. For example, Mathur et al. (2018) found that relative water content (RWC) of leaf was 93% in AMF inoculated wheat but declined to 27% in control (drought-stressed plants) while Abdel-Salam and co observed that plants grown under higher levels of drought stress exhibited more benefits from colonization with mycorrhizal fungi. Furthermore, there was a positive association between AMF colonization and increment of the nutrients content in shoot and root of damask rose plants, especially at higher levels of drought stress. These findings show that under drought stress conditions, plants depended highly on the presence of AMF which mitigated the damaging effects of drought stress on plant growth.

The importance of AMF inoculation is not limited to drought resilience of plants, as there are research suggestions that show that AMF could potentially increase
the uptake of nutrients and improve the yield of crops (Cardoso & Kuypers, 2006). For instance, Nzanza et al. (2012) found that inoculating tomato (Solanum lycopersicum L.) with AMF before sowing increased the percentage of extra-large fruit by about 8% as compared to the uninoculated plants.

In addition, Iglesias et al. (2011) reported that both Theobroma cacao and Igna. edulis seedlings had increases in leaf production after AMF inoculation. Their study revealed that Theobroma cacao seedlings with the conspecific AMF inoculum were 125% taller than the control seedlings at 16 weeks after inoculation. They attributed such good growth to the AMF infected roots, the development and spread of the AMF intraradical hyphae and extraradical hyphae. Such positive effect on plants could be due to the multiple role of extraradical hyphae in the transport of water and essential minerals (e.g. P), spore production, soil aggregation, and host plant protection from pathogen and its ability to reach out of the depletion zone that is beyond the reach of plant roots (Zhu et al., 2001).

Moreover, soil salinity has become an emerging challenge to cocoa farmers; because of the introduction of irrigation and the increase in the amount of evaporation (Akinrinde & Ayegboyin, 2006), which cause increased salt concentration in soils (Mahajan & Tuteja, 2005). Salinity suppresses general growth of plants due to a low osmotic potential especially during germination, emergence and early seedling growth (Yadav et al., 2019). For instance, it has been established that saline soils limit root development and growth of cocoa (Yara Ghana report, 2020b), thus, making it less resilience to the impact of drought. Fortunately, preliminary studies show that association of AMF showed beneficial effect on root morphology of citrus tangerine seedlings and enhanced the characters like root length, root-projected area, root surface area and root volume under salinity (Wu et al., 2010). In addition, Balliu et al. (2015) found that inoculation with commercial AMF during nursery establishment contributes to alleviation of salt stress by maintaining a favorable nutrient profile, thus, recommended that nursery inoculation of AMF seems to be a viable solution to attenuate the effects of increasing soil salinity levels.

A range of species of AMF have been identified to be associated with cocoa (Bae et al., 2008; Droh et al., 2016; Lahive et al., 2019; Ramirez et al., 2016; Soumaila et al., 2012). This creates a good opportunity to explore the use of AMF in enhancing cocoa seedling establishment in West Africa. The plethora of research that suggest that preconditioning of young seedlings with efficient arbuscular mycorrhizal fungi (AMF) makes plants stronger and helps in their establishment in fields (Cekic et al., 2012; Jha et al., 2014; Navarro Garcia et al., 2011; Shi et al., 2012) reiterate our hypothesis that the concept could be applied to tree crops like cocoa seedlings in the wake of drought stress caused by climate change. This innovation could result in superior and stronger growth of cocoa seedling and improve their establishment on farmers’ fields, with the potential to reflect in higher cocoa yield and improved living conditions of the majority of people that depend on the cocoa sector.

4. Conclusions and Perspectives for Future Studies

Although much is known on the general role of potassium in plants, very small number of studies (e.g. possible role for potassium in mediating cacao seedling responses to drought), if any at all, has been done to assess the effectiveness in using either K or AMF or their combination in building the drought resilience of cocoa at the seedling phase. This is important since knowing the synergy in potassium-native AMF interaction could help improve cocoa seedling establishment and growth under water stress conditions. The current established K rates for cocoa are meant for effective growth of the plant (Afrifa et al., 2010; Van Vliet & Giller, 2017; Yara Ghana report, 2020a). It is however imperative to further understand the rates of potassium fertilizers that will improve the physical (e.g. cell wall turgor, roots growth), physiological (e.g. respiration) and biochemical (e.g. Proline, polyamines, enzymatic) characteristics of cocoa seedlings to alleviate water stress.

In addition, further in-depth studies need to be conducted to develop better K recommendations based on soil types, location specific and current cocoa varieties. When this is developed, it will ensure sustainable yield and avert the practice of open/general K recommendation for cocoa farmers which has the potential of over application or under application. This is essential as excess K shortens life and accelerates leaf fall of cocoa trees, adds as extra cost to the already resource-constrained cocoa farmers and could affect the environment through potassium leaching. Furthermore, soil conditions of most cocoa growing regions are changing and salinity has become an emerging challenge in soil fertility management. This is exacerbated by the current poor distribution of rainfall and the promotion of irrigation for adoption by some cocoa farmers. It is imperative for cutting edge scientific studies to be developed to help in drought resilience under saline conditions. AMF research provides a good opportunity to explore in that regard. There is the need to change cocoa breeding strategies, which currently focuses on breeding cocoa genotypes with higher survival rate and productivity under
drought condition. Cocoa breeding strategies should focus more on breeding for climate resilient cocoa genotypes with emphasis on higher efficiency in K utilization and/or AMF colonization. This way, farmers will need to apply lower rates of K to achieve more drought resilient cocoa trees with higher seedling establishment under envisaged changes in climate.

**Availability of data and material**
Not Applicable

**Code of availability**
: Not Applicable

**Acknowledgements**
We thank the German Academic Exchange Service (DAAD) for their financial and mentorship support for this postdocs programme in Ghana, Africa. We also thank the Department of Agroforestry, Kwame Nkrumah University of Science and Technology, Ghana for hosting the postdoc student and providing field for the experiment. Lastly, we are grateful to Tessenderlo Kerley International, part of Tessenderlo Group, Belgium for providing us K-Leaf and Granupotasse fertilizers for the experiment in Ghana.

**Disclosure statement**
No potential conflict of interest was reported by the authors.

**Funding**
This work was supported by German Academic Exchange Service (DAAD) under the Climate Research for Alumni and Postdocs in Africa, 2020 (57516494).

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**Public Interest Statement**
Ghana is the second leading producer of cocoa in the world. Over six million Ghanaians depend on the cocoa sector as their source of livelihood. Unfortunately, climate change, especially drought, is currently the most critical factor affecting cocoa production.

Our idea is to use plant biostimulants as a means to improve the soil fertility, enhance cocoa seedling resilience to drought for improved yield. The current methods of enhancing cocoa seedling resilience to drought and survival is through breeding of drought resistant varieties, however, this approach is still at the infant stage and requires long period of time to validate results. Our approach provide solution to cocoa seedling mortality within a short period and integrate sustainable method of cocoa production which is easier for farmers to adopt. In addition, our approach is environmentally friendly and it could be considered as a climate smart soil fertility management.

**Summary of group key research activities**
The Department of Agroforestry conducts research that involve integration of trees/shrubs into traditional agriculture cropping systems, soil fertility improvement, climate change adaptation and plant biostimulants. We envisage that when the right woody perennials are selected and integrated with crops, they could help reclaim degraded lands/soils, improve soil fertility, reduce greenhouse gases emission and help farmers reduce the application of inorganic fertilizers, protect the environment, reduce cost of production and improve profitability of farming.

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