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The role of *Tithonia diversifolia* in sustaining crop productivity in acid soils

Andre Sparta[1, 4*], Jajang Sauman Hamdani[2], Yuyun Yuwariah[2] and Eliana Wulandari[3]

[1] *Padjadjaran University, Agricultural Science Study Program, Faculty of Agriculture, West Java, Indonesia*
[2] *Padjadjaran University, Departement of Agronomy, Faculty of Agriculture, West Java, Indonesia*
[3] *Padjadjaran University, Departement of Agricultural Social Economics, Faculty of Agriculture, West Java, Indonesia*
[4] *Indonesian Agency for Agricultural Instrument Standardization, Jakarta, Indonesia*
[*]*Corresponding author:* andre21003@mail.unpad.ac.id

Abstract

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Acid soils with high distribution around the world, both in temperate and tropical areas, are being used for agricultural activities to support food production. In order to utilize plant productivity in acid soils, organic material such as *Tithonia diversifolia* is being used to solve several constraints in acid soils. This article focuses on the use of *T. diversifolia* in acid soils and its benefit in supporting plant productivity in these kinds of soils. Published literature related to potency *T. diversifolia* to solve several problems in acid soils were collected from database SCOPUS (www.scopus.com), Google Scholar (https://scholar.google.com/), and others. We found that: 1) *T. diversifolia* improves the physical properties of acid soils by reducing soil bulk density and improving soil porosity; 2) *T. diversifolia* improves the chemical properties of acid soils by reducing soil acidity and improving soil reaction, as well as soil available nutrients; 3) *T. diversifolia* potentially reduces heavy metal contamination in acid soils; 4) *T. diversifolia*, combined with other elements, can potentially mitigate greenhouse gas emissions in acid soils; and 5) *T. diversifolia* contributes to improving plant productivities in acid soils.

Keywords: acid soils; plant productivity; *Tithonia diversifolia*

Introduction

To fulfill the rapid increase in food consumption, the agricultural sector needs to intensify land productivity in cropland areas (Kopittke et al., 2019), including acid soil (Kumar et al., 2021). Acid soils are widespread all over the world (Bian et al., 2013); in both temperate and tropical areas (Behera & Shukla, 2015), and occupy approximately around 30% of global ice-free land area (Fageria & Nascente, 2014; Gurmessa, 2021). The distributions of these soils are divided into two main areas: the southern tropic belt (dominated by oxisols and ultisols) and the northern belt (dominated by inceptisols, alfisols, histosols, and spodosols) (von Uexküll & Mutert, 1995). Furthermore, these types of soils are widely distributed in South-East Asia, northern sections of Europe and Eurasia, northern and eastern regions of North America, and Central and South Africa (Montanarella et al., 2015).

Acid soils contain several constraints that can suppress plant growth and development and impair agricultural yield (Dai et al., 2017). These kinds of soils are characterized by low reaction (low pH) in the top layer of soils (Dai et al., 2017), have poor fertility of nutrients (deficiencies of phosphorus, calcium, magnesium, and potassium), high toxicities of iron, manganese, and aluminum (Tang et al., 2013; Wang et al., 2011), and have low organic matter (Berihun et al., 2017). Furthermore, acid soils are susceptible to erosion due to their low aggregate stability (Yulnafatmawita et al., 2013). This state emerges as a result of intensive weathering and numerous anthropogenic activities in these kinds of soils (Jiang et al., 2012).

Soil management is a means of managing soil to provide better growth and development of plants, as well as improving plant productivity. Acid soils must be appropriately maintained to promote plant growth and development. Liming is a common approach for managing acid before planting (Fageria & Nascente, 2014). Liming has been proven in several studies to enhance nutrient availability (Barman et al., 2014), soil pH (Kisinyo, 2012), and plant production (Asrat et al., 2020). Liming, on the other hand, is impractical in many nations because of its price and limited availability (Wang et al., 2011). The slow-moving flow of lime into the subsurface soil can also render liming inefficient (Tang et al., 2013). Additionally, liming without additional organic material can potentially result in a nutritional imbalance in newly developed areas (Santri et al., 2019). As a result, an efficient and effective method for preparing acid soils for agricultural uses is required.

Several research have suggested that using organic materials may be one technique for promoting plant growth and development in acidic soils (Fageria & Nascente, 2014). The application of organic materials into acid soils can improve soil pH, reduce exchangeable Al^{3+}, reduce exchangeable acidity, improve soil exchangeable base cation, improve P availability, and improve crop productivity (Aboyeji et al., 2019; Adekiya et al., 2021; Agbede et al., 2014). *Tithonia diversifolia* is a multifunctional plant that belongs to the Asteraceae family. This plant leaves biomass contains 3.5% nitrogen, 0.37% phosphorus, and 4.1% potassium, as well as nutrients that are greater than in other organic materials (Jama et al., 2000). The biomass of this plant decomposes rapidly with the readability of nitrogen and other nutrients two or three weeks after the plant has been incorporated into the soil (Mwangi & Mathenge, 2014). Due to the invasive characteristics and high adaptation ability of *T. diversifolia*, this plant is easy to grow in many environmental conditions (Kato-Noguchi, 2020). Based on its characteristic, *T. diversifolia* undoubtedly represents a solution to minimize or solve the problem in acid soils and promote plant growth, development, and productivity.

This article focuses on the use of *T. diversifolia* in acid soils and its benefits in promoting plant productivity in these types of soils. Acid soils, with their characteristics of low soil reaction/pH (high soil acidity), low macronutrients, low organic matter, and high toxicities of Al, Mn, and Fe, need to be managed properly through simply access and abundant availability of organic material (*T. diversifolia*). The review assesses the impact of *T. diversifolia* on soil physical properties, soil chemical properties, soil heavy metal contamination, carbon sequestration, and plant productivity in acid soils.

Tithonia diversifolia Properties

Tithonia diversifolia (Hemsl) A. Gray, a native shrub from Mexico and South America, is a member of the Asteraceae family (Agbede et al., 2014). Due to its invasive characteristics, this plant spreads and develops in more than seventy countries around Australia, Africa, North America, and Asia (Obiakara & Fourcade, 2018). In the past, *T. diversifolia* was known only as an ornamental plant. However, over the past decade, researchers have extensively studied *T. diversifolia* and have reported its various advantages. *T. diversifolia* is known as a multi-purpose plant. It is suggested for animal diets due to the nutritious value of its biomass (Ruíz et al., 2014). Furthermore, this shrub plant is also used for antimicrobial, antimalarial, anticancer, and other medicinal purposes (Omokhua et al., 2018; Rizkawati, 2021). Additionally, the bioactive compound in this plant has also been discovered to control several pests (weevil, and termite) (Gitahi et al., 2021) and to suppress several weeds (Ajayi et al., 2017).

Several studies have shown that the introduction of *T. diversifolia* biomass into the soil can improve soil fertility. Biomass of this plant contains macronutrients, such as nitrogen, phosphorus, potassium, calcium, and magnesium that are beneficial for plant growth and development (Agbede et al., 2014; Ngosong et al., 2016; Opala et al., 2014). Moreover, recent studies have shown that biomass *T. diversifolia* has a total nitrogen concentration in the range of 2.26 – 4.52%, phosphorus concentration in the range of 0.2 – 0.95%, potassium concentration in the range of 2.13 – 5.00%, calcium concentration in the range of 1.81 – 3.52%, and magnesium concentration in the range of 0.04 – 5.41 (Table 1). The biomass of this plant also contains micronutrients such as zinc, iron, manganese, copper, and boron (Reis et al., 2016); these nutrients are also essential for plant growth and development even in small concentrations.

Even in low soil fertility, *T. diversifolia* can produce high amounts of biomass every year, because it has high adaptation to several soil conditions (Ruíz et al., 2014). This kind of shrub also produces more biomass compared to other plants, which is attributed to different methods of acquisition of soil nutrients or more effective utilization of soil resources (Jorge Mustonen et al., 2012). *T. diversifolia* grows rapidly and has a fast recovery after cutting. Cutting frequency increases the

Table 1. N, P, K, Ca, and Mg concentrations in *Tithonia diversifolia* biomass

N, %	P, %	K, %	Ca, %	Mg, %	Source
3.3	0.53	3.89	3.41	0.04	(Agbede et al., 2014)
4.23	0.41	2.64	1.81	0.38	(Opala et al., 2014)
3.3	0.31	5.0	nd*	nd	(Asbon et al., 2015)
4.52	0.55	3.22	nd	nd	(Ngosong et al., 2016)
2.26	0.95	2.13	nd	nd	(Kolawole, 2016)
3.95	0.53	3.16	3.52	5.41	(Aboyeji et al., 2019)
3.2	0.3	3.1	2.8	0.6	(Imani Wa Rusaati et al., 2020)
3.0	0.2	2.9	2.2	0.6	(Ndung'u et al., 2021)

nd*, not determined

biomass production of this plant. A study proved that the foliage biomass of *T. diversifolia* rose with increasing pruning frequency, whereas wood biomass decreased and *vice versa* (Senarathne et al., 2019). Furthermore, the biomass of this plant can provide earlier macronutrients, which are beneficial for plant growth and development. Due to the low C/N ratio and high moisture content, *T. diversifolia* biomass has an accelerated decomposition and mineralization process, compared to other plant biomass (Aboyeji et al., 2019).

The Role of *Tithonia diversifolia* in Sustaining Crop Productivity in Acid Soils

The main objective of the agriculture in current decade is to solve various challenges in acid soils in order to preserve crop productivity in these types of soils. Multiple research projects on *T. diversifolia* have been performed over the last two decades, providing some understanding of the advantages and the role of *T. diversifolia* in the agricultural sector in a range of soil conditions, including acid soils. *T. diversifolia* biomass improves plant growth and development as well as productivity in acidic soils by addressing numerous limiting variables. High biomass production and high nutrient contents in *T. diversifolia* leaves are the crucial factors that determined the function of this shrub plant (Aboyeji et al., 2019; Adekiya et al., 2021). This plant's biomass led to increased soil organic matter, assisting in improving soil conditions in acidic soils (Hafifah et al., 2016). Improving soil organic matter improves soil physical, biological, and chemical characteristics. Improving numerous soil properties, particularly in acidic soils, will allow for greater nutrient flow and plant growth in these types of soils. Although some research provides inconsistent findings, several studies still generate beneficial results when *T. diversifolia* is incorporated in these low fertility soils. The inconsistent findings during *T. diversifolia* introduction in acid soils probably due to low input biomass of this plant into soil and short-term observation during the experiment.

Improve Physical Properties of Acid Soils

The introduction of *T. diversifolia* in the soils, either as a direct application in the soil or fallow systems, potentially improves the physical properties of acid soils (Table 2) (Adekiya et al., 2021; Bilong et al., 2017). Several experiments showed that plants can grow and develop better in acidic soils after the integration of *T. diversifolia* biomass into the soil due to the reduced soil bulk density (Dayo-Olagbende et al., 2019; Senarathne et al., 2019). *T. diversifolia* fallow treatment reduced the bulk density of Alfisol soil by approximately 22% compared to control (Adekiya et al., 2021). Agbede et al. (2014) discovered a reduction in soil bulk density after incorporating 12.5 t/ha of *T. diversifolia* mulch. Soil bulk density describes the compactness of the soil, which is related to other soil physical characteristics and soil health. The value of soil bulk density is not fixed; it can change based on soil management and climate conditions (Logsdon, 2012). Reducing the compactness of the soil may allow root plants to grow and develop favorably, and facilitate soil infiltration to absorb water and nutrition. Aboyeji et al. (2019) discovered an increase in root characteristics following the incorporation of *T. diversifolia* biomass into the soil.

Several studies also found that using *T. diversifolia* enhanced other soil physical properties. Bilong et al. (2017) discovered an increase in total soil porosity and water-holding capacity following the incorporation of *T. diversifolia* green manure into the soil. In comparison to the control, a 10 t/ha biomass application of this plant improved total soil porosity and water holding capacity by 6.8% and 4.7%, respectively. The use of inorganic fertilizer in conjunction with *T. diversifolia* as a mulch increased total soil porosity, infil-

Table 2. Summaries of soil and crop response to *T. diversifolia* application

Application	Effect	Source
Green Manure	Improves seed germination, plant growth, plant production, plant product quality, total soil porosity, water holding capacity, agronomic phosphorous use efficiency, partial factor productivity rate, water holding capacity, agregat stability, soil organic carbon, soil N, P, and K, soil pH, microbial activities, aggregate percentage, aggregate stability index, and reduces soil bulk density, alumunium solubility	(Aboyeji et al., 2019; Ahmat et al., 2014; Asbon et al., 2015; Endris, 2019; Gervais Bilong et al., 2017; Hafifah et al., 2016; Imani Wa Rusaati et al., 2020; Omenda et al., 2020; Opala et al., 2014; Rioba et al., 2020; Senarathne et al., 2019; Wahyudi & Handayanto, 2015; Yulnafatmawita & Anggriani, 2013)
Fallow System	Improves total soil porosity, moisture content, soil organic matter, soil N, P, K, Ca, and Mg, CEC, soil pH, plant production and reduce soil bulk density	(Adekiya et al., 2021)
Mulch	Improves soil temperature, soil organic matter, soil N, P, K, Ca, and Mg, moisture content, infiltration rate, total soil porosity, cation exchange capacity, phosphorous uptake efficiency, phosphorous utilization efficiency, soil pH, plant production, and reduces soil bulk density	(Agbede et al., 2014; Dayo-Olagbende et al., 2019; Endris, 2015; Jorge-Mustonen et al., 2013; Mustonen et al., 2014; Ngosong et al., 2016)
Liquid Extract	Improves plant growth, plant production, and suppress weed	(Ajayi & Rasheed, 2017; Chikuvire et al., 2013)
Compost	Improves soil pH, soil organic carbon, soil N, P, and K, plant production, and reduce heavy metal contamination (Pb, Cd, Cr, Zn, Cu)	(Adejumo et al., 2011; Hakim & Mala, 2012; Kolawole, 2016; Mlangeni et al., 2013)
Living plant	Phytoremediation	(Ayesa et al., 2018; Kekere et al., 2020; Olawepo et al., 2020)

tration rate, and soil moisture content (Dayo-Olagbende et al., 2019). However, as compared to the control, the high rate of *T. diversifolia* mulch application had a more pronounced consequence. Another study finding was that *T. diversifolia* treatment increased soil bulk density, total soil porosity, and soil aggregate stability (Hafifah et al., 2016).

Additional organic materials in soils, such as *T. diversifolia* biomass, improve soil organic matter in acidic soils. The increase in soil organic matter as a result of *T. diversifolia* biomass decomposition by soil microorganisms, improved soil physical properties on acidic soils (Hafifah et al., 2016). Adekiya et al. (2021) observed an increase in soil organic matter in *T. diversifolia* applications, whether alone or in combination, which resulted in improvement soil physical parameters. Soil organic matter is widely regarded to be beneficial for increasing soil texture and nutritional value (Imani Wa Rusaati et al., 2020). Furthermore, the presence of a high quantity of organic matter in the soil may enhance soil structure, increase the aeration and infiltration of rainwater, and have a high water retention capacity (Senarathne et al., 2019). Additionally, *T. diversifolia* biomass incorporation into acid soils also promoted microbial activities that are beneficial to soil physical characteristics (Senarathne et al., 2019).

Improve Chemical Properties of Acid Soils

The addition of *T. diversifolia* to acid soils may improve the chemical properties of this poor soil. *T. diversifolia* biomass improved soil pH, C/N ratio, and the soil availabilities of N, P, and K; it also improved cation exchange capacity (CEC) (Table 2). For example, compared to the control, the application of *T. diversifolia* mulch in Alfisol enhanced the value of soil N and P; however, the increase in exchangeable K, Ca, and Mg were only observed in the application of *T. diversifolia* mulch up to 7.5 t/ha (Agbede et al., 2014). This shrub may provide adequate nutrients to low-fertility soils (Chikuvire et al., 2013). Additional inorganic fertilizer in the soil can be one of the solutions to the problem of poor fertility soils. However, farmers' ability to acquire this form of fertilizer is limited due to its low availability and expensive cost (Adekiya et al., 2021). Furthermore, constant use of inorganic fertilizer decreases soil pH and soil fertility. Consequently, organic materials with high availability and a high composition of nutrients, such as *T. diversifolia*, may provide significant nutritional support in acidic soils.

Numerous studies revealed that using *T. diversifolia* was more beneficial to the plant and soil than using other organic sources. Experiment Agbede et al. (2014) discovered that *T. diversifolia* mulch enhanced soil nutrient retention better than *Chromolaena odorata* mulch. Adekiya et al. (2021) obtained a similar finding. This study discovered higher maize leaf nutrient contents (N, P, K, Ca, and Mg) in *T. diversifolia* fallow compared to *Cajanus cajan* and *Pennisetum purpureum* fallow systems. Considering biomass *T. diversifolia* has a higher biomass production and nutritional content than other organic sources, this shrub plant application provided better plant growth and soil qualities. In comparison to *T. diversifolia*, another organic source with high nutritional content is *Parkia biglobosa*. However, Aboyeji et al. (2019) discovered that using *T. diversifolia* led to a better radish yield when compared to *Parkia biglobosa*. *T. diversifolia* has a faster rate of mineralization and decomposition than *Parkia biglobosa*, which results in faster nutrient availability for the plant once *T. diversifolia* is introduced into the soil.

Low soil reaction (pH) is one characteristic of acid soils that may determine plant growth and yield. Several studies on acid soils discovered a rise in soil pH after incorporating *T. diversifolia* into the soil. At 42 days after incubation, compared to control, soil pH in sandy clay loam, sandy loam, and loamy sand improved by 0.43 units, 0.53 units, and 1.20 units, respectively (Kolawole, 2016). Experiment Ngosong et al. (2016) also found that after applying plant residue of *T. diversifolia*, soil pH increased by 2.42 units compared to the control. Increasing soil pH following organic material application is connected to the exchange process between basic ions (OH-) and acidic ions (H+) (Hafifah et al., 2016). Several organic materials may produce hydroxide ions (OH-), resulting in a high concentration of these ions and raising soil pH to a more neutral level. According to Wahyudi & Handayanto (2015), *T. diversifolia* pruning was more effective than *Gliricidia sepium* pruning in improving soil pH because it produced more organic acids (humic acid and fulvid acid).

Phosphorus availability is also one of the major constraints in acid soils (Endris, 2019). Even though *T. diversifolia* has a low phosphorus content, it can enhance the available phosphorus in the soil, thereby resolving that significant constraint. An experiment showed better yield and nutrient use efficiency metrics when *T. diversifolia* with phosphorus content was applied into soil compared to phosphorus content from inorganic fertilizer (TSP) (Endris, 2019). This plant applies to enabling root development as well as the rapid processing of phosphorus and other nutrients (Scrase et al., 2019). The rapid recycling of nutrients following *T. diversifolia* application is related to enhanced microbial activity, as proven by (Senarathne et al., 2019). Microbial activities promote soil organic P mineralization under low to moderate P sorption capacity, resulting in the formation of inorganic P at a higher pace than P sorption (Kolawole, 2016). The rise in soil P following organic matter treatment is also connected to the involvement of organic acids produced during the decomposition process (Hafifah et al., 2016).

Several *T. diversifolia*-related research discovered that soil chemical characteristics in acidic soils had not improved. Mustonen et al. (2014), for example, found a decrease in soil pH after incorporating *T. diversifolia* into the soil. This state can emerge as a result of short-term use and low organic material input (Jorge Mustonen et al., 2012). Hafifah et al. (2016) also observed a decrease in soil pH during the decomposition process as compared to the initial soil state. However, these experiments still resulted in satisfactory yields compared to other treatments. A study by Jorge-Mustonen et al. (2013) also found no improvement in soil chemical characteristics when *T. diversifolia* was used as mulch in acidic soils. This experiment, however, produced a significant yield of beans due to high nutrient use efficiency, particularly phosphorus. Similarly, Ngosong et al. (2016) discovered that applying *T. diversifolia* plant parts as a mulch in acidic soils enhanced tomato yields more than using inorganic fertilisers. This investigation discovered no significant improvement in soil chemical properties when *T. diversifolia* biomass was mixed into acid soils, with the exception of soil pH.

Reduce Heavy Metal Contamination

Continuous application of chemical fertilizers, pesticides, and other agricultural practices creates heavy metal contamination in the soil. Heavy metal levels such as lead, zinc, cadmium, and so on rise from year to year as a result of these activities. This situation not only limits plant growth and production, but it also endangers human health since this heavy metal enters the food chain through consumption (Ji et al., 2018). Hence, an economical and ecologically friendly alternative involving living plants is required to reduce metal deposition in the soil. Several living plants, including *T. diversifolia*, are employed for phytoremediation in contaminated soils. Because *T. diversifolia* was not used for human consumption, heavy metal accumulation in root and shoot tissue could not represent a risk to the human population. As a result, this plant may be among the most promising possibilities for reducing heavy metal pollution in polluted soils (Kekere et al., 2020).

Despite the lack of information on the use of *T. diversifolia* as phytoremediation in acid soils, various investigations in other soil conditions demonstrate that this plant can reduce heavy metal contamination in polluted soils (Table

2). According to Ayesa et al. (2018), *T. diversifolia* has the potential for phytoremediation in soils polluted with hazardous chemicals such as lead, zinc, copper, cadmium, and iron. Olawepo et al. (2020) discovered that *T. diversifolia* reduced Cu, Cr, Cd, Pb, and Ni levels in contaminated soils by 85%, 96%, 88%, 94%, and 86%, respectively. Furthermore, bioaugmentation with *Globus clarum* improves this plant's ability to reduce Zn and Pb levels in polluted soils (Kekere et al., 2020). *T. diversifolia* with phytoextraction approach entails removing heavy metals from soil and depositing them in above and below plant tissue.

Several research also discovered that *T. diversifolia* application compost and green manure may be utilized to remediate contaminated soil. Adejumo et al. (2011) discovered that applying 40 tonnes of compost *T. diversifolia* per hectare reduced heavy metal levels contamination (Pb, Zn, Cu, Cd, and Cr) in acid soil. Another investigation on Fe contamination in rice fields conducted by Hakim & Mala (2012) revealed a decrease in Fe^{2+} solubility after the introduction of *T. diversifolia* biomass in various combinations into the soils. Furthermore, Wahyudi & Handayanto (2015) discovered that applying *T. diversifolia* to the soil reduced aluminium solubility. Organic acid production from *T. diversifolia* during the decomposition process contributed in reducing metal solubility in soils (Hakim & Mala, 2012). The efficiency of *T. diversifolia* in decreasing heavy metal pollution, however, is dependent on a number of conditions. The experiment conducted by Aboyeji et al. (2022) yielded contradictory results. This investigation discovered a rise in heavy metal levels after applying *T. diversifolia* to tomatoes for two years in a row; however, the heavy metal concentrations remained below the allowable range.

Mitigate Greenhouse Gas Emissions

Agricultural activities in both developing and developed countries contribute to climate change by increasing greenhouse gas emissions (Gilbert, 2012; Tubiello et al., 2013). However, agricultural sectors are the main contributors as food providers to the human population. Thus, a solution is required to produce sufficient food from agricultural activities in line with minimizing or mitigating greenhouse gas emissions from these activities. Detailed studies regarding the mitigation of greenhouse gas emissions through the addition of *T. diversifolia* are still limited. However, several studies have indicated that this shrub plant has the potential to mitigate greenhouse gas emissions (Table 2). *T. diversifolia* can significantly reduce greenhouse gas emissions by sequestering large amounts of carbon in the soil. Ngosong et al. (2016) discovered a considerable increase in soil organic carbon in the application of *T. diversifolia* mulch compared to the control and application of inorganic fertilizer. The combination of 60 kg ha^{-1} urea and 60 tons ha^{-1} *T. diversifolia* mulch increases soil organic carbon by 350% when compared to the control (Dayo-Olagbende et al., 2019). Omenda et al. (2020) also reported an increasing trend of total organic carbon in acid soils after adding *T. diversifolia* biomass to the soil.

The ability of soil to sequester carbon is affected by various factors, including the initial amount of carbon, the C/N ratio, and the stability of the carbon component. Hafifah et al. (2016) observed that green manure *T. diversifolia* increased soil organic carbon more than cow manure. This finding might be related to the higher carbon content of *T. diversifolia* (31.76%) than cow dung (8.18%). Mlangeni et al. (2013) discovered a similar finding in their investigation. In this study, composts were created from the combination of *T. diversifolia* and maize stalk. The experiment demonstrated that high initial soil carbon was positively related to soil organic content. Furthermore, this experiment also discovered that a low C/N ratio and the stability of the carbon fraction resulted in a high soil organic carbon content.

T. diversifolia also contributes to minimizing greenhouse gas emissions by reducing or eliminating the use of inorganic fertilizer in agricultural practices. Inorganic fertilizer application to soil could potentially improve greenhouse gas emissions. For example, NPK treatment in cauliflower decreased organic carbon in the soil compared to the initial soil condition (Hafifah et al., 2016). *T. diversifolia* treatment, on the other hand, improved soil organic carbon in this experiment. *T. diversifolia* also resulted in a better yield as compared to NPK treatment. Other studies by Fungo et al. (2017) and Fungo et al. (2019) discovered that the sole application of *T. diversifolia* cannot reduce CO_2, NH_3, and N_2O emissions in acid soils. On the other hand, *T. diversifolia* mixed with charcoal and urea reduced overall NH_3 emissions by approximately 18% (Fungo et al., 2019). This finding suggests that *T. diversifolia* must be paired with other elements in particular conditions to demonstrate its potential for reducing greenhouse gas emissions.

Improve Plant Productivity

The attributes of acid soils, such as low pH (von Uexküll & Mutert, 1995), low resources of organic matter (Berihun et al., 2017), poor availability of macronutrients (phosphorus, calcium, magnesium, and potassium), and high toxicities of heavy metal (Dai et al., 2017; Tang et al., 2013; Wang et al., 2011), create many constraints in the soil that can obstruct the plant growth and development and can result in a low yield of plants compared to neutral soils

(Fageria & Nascente, 2014). Many studies have shown that the application of *T. diversifolia* biomass (alone or in combination with other fertilizers) can resolve those constraints and be beneficial for plant productivity in acid soils (Table 3). The beneficial results in acid soils after the introduction of *T. diversifolia* into soil created an opportunity to produce sufficient food for the human population in the conditions of limited resources.

T. diversifolia can improve food productivity in acid soils because it has a high concentration of beneficial nutrients in its biomass (Aboyeji et al., 2019; Asbon et al., 2015; Kolawole, 2016; Ngosong et al., 2016; Opala et al., 2014). Low nutrient concentrations, especially phosphorus, is a characteristic of acid soils, and acts as a barrier to plant growth and development (Endris, 2019). Additional nutrients from inorganic fertilizers can be one of the solutions to this problem. However, due to expensive prices and limited availability, these fertilizers are unaffordable for small-scale farmers. Moreover, the continuous application of inorganic fertilizer increases soil acidity (Ahmat et al., 2014). Thus, with a high concentration of nutrients in its biomass, *T. diversifolia* becomes an attractive alternative to replace chemical fertilizers.

Several experiments have concluded that *T. diversifolia* biomass can be a replacement for inorganic fertilizer. The amendment of soil with *T. diversifolia* as mulch produces a higher tomato yield than inorganic (NPK) application (Ngosong et al., 2016). Similar results were also found in experiments on maize (Endris, 2019) and rice (Imani Wa Rusaati et al., 2020). *T. diversifolia* biomass provides higher nutrient use efficiency after application into acid soils, compared to other applications. Therefore, even if a similar amount of nutrients is being applied, the application of the biomass of this plant can result in better performance and higher yield (Endris, 2019). However, some experiments showed that the application of *T. diversifolia* still needs additional inorganic fertilizer to promote the optimal yield of the plant. Compared to other treatments (such as poultry manure and several applications of inorganic fertilizers; the application of *T. diversifolia* biomass with additional TSP results a higher yield of kales (Mwangi & Mathenge, 2014). Other experiments with maize also showed that high yields of plants are achieved after the combined application of *T. diversifolia* with inorganic fertilizers (Ahmat et al., 2014; Dayo-Olagbende et al., 2019; Endris, 2019).

Sufficient plant production in acid soils after the incorporation of *T. diversifolia* into soils may also occur due to improving soil pH, decreasing soil acidity, enhancing soil texture and structure, and improving soil available P. A result of the experiment by Ahmat et al. (2014) showed that the application of rock phosphates with *T. diversifolia* enhances shoot dry matter of maize, due to improving the soil pH and improving soil texture and structure. Another study also revealed that *T. diversifolia* has the potential to improve the potassium content in the soil, which produces a higher yield of tomatoes (Ngosong et al., 2016). *T. diversifolia* also improves phosphorus use efficiency in the soils (Endris, 2019). Although some experiments indicated that the application of *T. diversifolia* does not affect some of the properties in the soil, they nevertheless resulted in a higher yield (Jorge-Mustonen et al., 2013; Mustonen et al., 2014). These experiments recorded that *T. diversifolia* biomass as

Table 3. Crop yield increased following the treatment of *T. diversifolia*

Treatment	Plant	Yield increases compared to control, %	Source
750 ml *T.diversifolia* per plant per week	Rape	133%	(Chikuvire et al., 2013)
7.5 ton ha^{-1} mulch *T.diversifolia*	Yam	73%	(Agbede et al., 2014)
10 kg ha^{-1} P from *T.diversifolia*	Maize	103%	(Ahmat et al., 2014)
4,3 ton ha^{-1} *T.diversifolia*	Kales	122%	(Mwangi & Mathenge, 2014)
8.15 ton ha^{-1} *T.diversifolia*	Cauliflower	77%	(Hafifah et al., 2016)
10 ton ha^{-1} *T.diversifolia*	Radish	228%	(Aboyeji et al., 2019)
60 kg ha^{-1} urea+3 ton ha^{-1} mulch *T.diversifolia*	Maize	76%	(Dayo-Olagbende et al., 2019)
20.3 kg ha^{-1} P from *T.diversifolia*	Maize	92%	(Endris, 2019)
10 ton ha^{-1} *T.diversifolia*	Cassava	84.8%	(Gervais Bilong et al., 2017)
5 ton ha^{-1} poultry feather+5 ton ha^{-1} *T.diversifolia*	Tomato	184.9%	(Adekiya, 2019)

a mulch does not improve the chemical properties of acid soils, however, there was a greater yield of beans. The high yield was still achieved because *T. diversifolia* can improve nutrient use efficiency in the soils, especially phosphorus use efficiency. Apart from increasing plant productivity, the application of *T. diversifolia* also improves the quality of plant products (Aboyeji et al., 2019; Rioba et al., 2020).

Conclusions

Our reviews showed that several experiments have been conducted relating to the role of *Tithonia diversifolia* in improving food productivity in acid soils. The application of *T. diversifolia* biomass improves both soil physical and soil chemical properties in the acid soil by reducing soil bulk density, reducing soil acidity, improving total soil porosity, and improving nutrient use efficiency. This plant also has a function in reducing heavy metal contamination, improving carbon sequestration, and mitigating greenhouse gas emissions. Moreover, integrating *Tithonia diversifolia* into the soil has contributed to greater yields in the acid soils.

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