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Recent Advances in the Use of *Tithonia diversifolia* Green Manure for Soil Fertility Management in Africa: A Review

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ABSTRACT

Tithonia biomass transfer was presented as a technology that would replenish infertile soils, enhance food security and eradicate poverty in Africa in the 1990s. Since then, a huge volume of research has been conducted and the agronomic effectiveness of tithonia unequivocally demonstrated. Its reported effects on soil properties have however been inconsistent. This has made it difficult to develop a predictive understanding of the effects of tithonia on soil properties. Socio-economically, tithonia failed to live up to the hype on its ability to increase the farmers' incomes. Adoption rates have been dismal mainly because of high labor costs associated with its use. Two decades later, poverty and food insecurity are still widespread in Africa despite the enormous research and extension efforts that were devoted to popularizing the technology.

Key words: Adoption, Socioeconomics, Soil, Tithonia research.

In the 1990's, soil fertility depletion was identified as the fundamental root cause of declining food production in Africa. It was postulated that irrespective of how effectively other constraints were remedied, food production would continue spiraling downward unless soil infertility was conclusively addressed (Sanchez and Leakey, 1997). At that time, fertilizer prices had escalated because of reduced government subsidies. The situation was exacerbated by lack of credit and delays in delivery of fertilizer due to poor transport and marketing infrastructure (Place *et al*., 2003) resulting in low fertilizer use. This renewed interest in the use of what were considered to be cheap locally available nutrient sources to replenish soil fertility (Kwesiga and Coe 1994). A variety of none traditional organic resources such as *Lantana camara*, *Calliandra calothyrsus*, *Leucaena leucocephala and Tithonia diversifolia* (tithonia), were subsequently tested in western Kenya and tithonia identified as the most promising (Gachengo, 1996). Tithonia leaves have a high concentration of N, P and K (Jama *et al*., 2000) and it was therefore touted as the panacea of the soil fertility problems and hence poverty in Africa.

Tithonia is an annual weed that originated from Mexico and is now found along major roads, paths and on abandoned farmlands in many parts Africa (Agbede *et al*, 2013). The abundance and adaptation of tithonia to various environments coupled with its rapid growth rate and very high vegetative matter turnover makes it ideal for soil rejuvenation (Olabode *et al*. 2007). It has been used as mulch, biomass transfer and improved fallows in soil fertility management. The biomass transfer system which involves growing tithonia along boundaries and contours of farms or collection of the same from off-farm niches such as roadsides and applying the leaves and tender stems on the fields mostly during planting (Place *et al*., 2002) has however received the most research attention.

Initial studies on tithonia biomass for soil fertility management were spearheaded by the International Centre for Research in Agroforestry (ICRAF) in western Kenya. These studies focused mainly on tithonia's ability to increase yields of maize. Dramatic increases in yields due to application of tithonia were observed but the mechanisms by which tithonia impacted positively on the yields were often not studied or properly understood. The explanations given for the better performance of crops treated with tithonia compared to inorganic fertilizers and other organic inputs were therefore largely speculative. A comprehensive review of these studies was published by Jama *et al*. (2000). Since then, a lot of research work on tithonia has been conducted in various parts of Africa and much effort devoted to understanding the biophysical processes underpinning its performance. In addition, socio-economic aspects of tithonia have now been studied and a large body of knowledge generated. This paper complements the review by Jama *et al*. (2000) by incorporating these advancements.

Effects of tithonia on selected soil physical properties

Bulk density

Bulk density (bd) signifies the compactness of a soil and determines the ease with which roots penetrate it, emergence of seedlings, water infiltration and percolation

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and the soil porosity. It has, therefore, often been determined in several tithonia studies. Results are however inconsistent. Some show no effect while others report significant reductions in bd due to tithonia use. For example, in Kenya, bd was not significantly affected by application of tithonia at 1.8 t ha^{-1}(Waswa *et al*., 2004) while in southwestern Nigeria, tithonia mulches reduced bd compared to unmulched plots (Agbede *et al*., 2014) but this reduction was only significant at higher (>10 t ha^{-1}) and not lower (< 7.5 t ha^{-1}) rates of application. Kolawole *et al*. (2014) similarly reported a reduction by about 3% on soils treated with 20 t ha^{-1} of tithonia compared with the untreated soils but at lower rates (<15 t ha^{-1}), there was no significant reduction. Hafifah *et al*. (2016), however, observed reduction in bd at a rate of 8.15 t ha^{-1}, a rate that would be considered low by Kolawole *et al*. (2014) (Table 1). The reduction in soil bd was attributed to increased soil organic matter (SOM) due to decomposition of tithonia by soil microorganisms (Adesodun *et al*., 2015). It is likely that at lower rates, insufficient SOM was generated to effect a reduction in bulk density.

Soil temperature and moisture

The effect of tithonia on soil temperature and moisture has been found to depend on its rate of application. Tithonia reduced soil temperature when applied at a rate of 20 t ha^{-1} but not at rates lower than 15 t ha^{-1} (Kolawole *et al*., 2014). Similar results were reported by Agbede *et al*. (2013). Reduction in temperature was often accompanied by increased moisture retention due to reduced evaporation. In southwest Nigeria, application of 7.5 t ha^{-1} tithonia significantly increased soil moisture content and reduced temperature irrespective of the tillage method (Agbede and Ogundele, 2015). Other studies have likewise reported increased moisture holding capacity especially at high rates of application (Atayese and Liasu, 2001; Agbede *et al*., 2014; Hafifah *et al*., 2016) (Table 1). This again is likely due to an increase in SOM which is colloidal and also buffers the soil against rapid changes in temperature.

Soil Structure

Soil structure influences multiple dimensions of soil such as infiltration, drainage and water holding capacity. Tithonia increased structural stability of highly erodible loamy sand compared to inorganic fertilizers but was less effective than poultry manure and composts (Adesodun *et al*., 2015). Hafifah *et al*. (2016) reported a similar improvement in soil structure by tithonia and cow manure (Table 1). An improvement in aggregate stability of Inceptisols, due to tithonia application, was attributed to an increase in SOM which acted as a cementing factor for soil particles (Guong, *et al*., 2010). In addition, the mulch stabilized the soil structure against raindrop impact and thereby prevented erosion, compaction and crusting of the soil (Agbede *et al*., 2014).

Effect of tithonia on selected soil chemical properties

Soil pH, exchangeable acidity and aluminum

In acidic soils, which are widespread in Africa, aluminum toxicity constrains crop production. The effects of tithonia on soil pH, exchangeable acidity and aluminum have therefore been extensively studied but results are contradictory. Soil pH has been reported to vary depending on rates of tithonia applied, soil type and time of sampling the soil after tithonia application. An increase in pH due to application of tithonia in both pot and field experiments have been reported by several authors. In an incubation study, Opala *et al*. (2012a) found that soil pH increased at 4 weeks after application of 33 t ha^{-1} of tithonia but the pH declined by the 9th week. Similar results were reported by Cong and Merckx (2005) with application of 88 t ha^{-1}. These rates are however extremely high and cannot be applied under normal farming conditions. Some of the field studies that have demonstrated an increase in pH with tithonia application are those of Ikerra *et al*.(2006) at rates of 2.5 to 7.5 t ha^{-1} in Tanzania, Shokalu *et al*. (2010) at 20 t ha^{-1} and Awopegba *et al*. (2017) at 5 t ha^{-1} in Nigeria. In addition to microbial decomposition that releases base cations, the rise in soil pH when undecomposed plant residues such as tithonia are applied to soils has been attributed to decarboxylation of organic anions which results in the consumption of protons (Tang *et al*., 1999).

In other studies, the pH of tithonia amended soils was not significantly changed (Chukwuka and Omotayo 2009;

Table 1: Effect of *T. diversifolia* green manure, cow manure and NPK on soil physical properties.

Treatments	Bulk Density (g/cm^3)	Total Porosity (%)	Aggregate Stability (%)	WHC (%)
Control	1.27c	45.38a	69.12b	37.85a
T. diversifolia (8.15 t ha^{-1})	0.94a	52.40cb	74.21d	39.80e
Cow manure (25.85^{-1})	1.06b	52.88d	69.68c	39.58d
NPK (1.35 t ha^{-1})	1.28c	45.31a	60.00a	38.16b
T. diversifolia + Cow manure	1.04b	50.82bc	78.60f	38.70c
T. diversifolia + NPK	1.00ab	51.88cd	75.35e	41.25f
Cow manure + NPK	1.05b	49.91b	84.10g	42.13g
T. diversifolia + Cow manure + NPK	1.04b	51.00bc	85.40h	41.25f
LSD 5%	0.06	1.71	0.09	0.24

Variables followed by similar letters in the same column indicate not significant in LSD 5% test.

Source: Hafifah *et al.* (2016).

Jorge-Mustonen *et al*., 2013). This was attributed to the short-term nature of the studies, low rates of tithonia used and nitrification with release of H^+ ions. However, Mucheru-Muna *et al*. (2014) observed a decline in soil pH in most of the tithonia treatments in Kenya after 13 cropping seasons. The pH decline is likely due to nitrification and release of H^+ as tithonia decomposes (Cong and Merckx, 2005).

An increase in soil pH was associated with decrease in exchangeable acidity and aluminum with tithonia application (Mukuralinda *et al*., 2011) because Al is precipitated at high pH as $Al(OH)_3$. Thus, tithonia applied at rates of 2.5, 5.0 and 7.5 t ha^{-1} significantly reduced exchangeable Al in field and incubation studies (Cong and Merckx, 2005; Opala *et al*., 2012a). In northern Zambia, Malama (2001) reported a decrease in exchangeable acidity and aluminum with application of 4.5 t ha^{-1} tithonia. However, in some cases, there was a reduction in exchangeable acidity and aluminum even when tithonia failed to increase pH because of tithonia's ability to chelate aluminum (Opala *et al*., 2012a).

Available phosphorus and phosphorus sorption

The ability of tithonia to reduce P sorption and increase its availability in soils attracted much interest because the preliminary studies were conducted in western Kenya where P deficiencies and high P sorption capacities are widespread. Tithonia reduced P sorption especially when applied at high rates (> 5 t ha^{-1}) (Nziguheba *et al*., 2002a; Ikerra *et al*., 2006; Opala *et al*., 2010) but failed to do so in others at low rates (< 2 t ha^{-1}) (Opala *et al*., 2007). The reduction in P sorption was attributed to a variety of mechanisms. These include; production of organic acids produced during the decomposition of tithonia which chelate with Al and Fe in the soil solution, thus preventing precipitation of the phosphate; the organic anions produced during the decomposition of tithonia may compete with P for the same adsorption sites and thereby increase P-availability in the soil and increase in pH which increases the negative charge on the soil thus repulsing the negatively charged orthophosphate ions (Iyamuremye *and* Dick, 1996; Nziguheba *et al*., 1998; Guppy *et al*., 2005). Available soil P also increased because it was released when tithonia mineralized (Partey, *et al*., 2010). In some studies, tithonia was as effective as inorganic phosphate fertilizer in increasing P availability (Opala *et al*., 2007). Tithonia however has a low P content and therefore it cannot be used as a P source for crops on a field scale. For example, in a study by Opala (2010), the amount of tithonia applied to supply 60 kg P ha^{-1} was 20 t. This amount of tithonia, would in addition supply about 600 kg N ha^{-1}, which is far in excess of the 70 kg N ha^{-1} that is recommended for maize in western Kenya. Focus thus shifted to using tithonia as an N source and supplementing it with inorganic P sources such as triple superphosphate and phosphate rock (PR).

With an aim of promoting the use of cheap locally available resources, the ability of tithonia to increase solubility of PR was investigated. It was initially hypothesized that during decomposition, tithonia produces organic acids that solubilize PR and therefore increase P availability (Jama and van Straaten, 2006). Later doubts were cast as to whether this was plausible because tithonia had been reported to increase soil pH in some studies and also had high calcium content which is negatively correlated with PR dissolution. Savini *et al*. (2006) confirmed that combining PRs with tithonia indeed depressed the dissolution of PRs and hence P availability.

Soil organic matter

Soil organic matter is central to the sustainability of soil fertility on smallholder farms in Africa and therefore the influence of tithonia on SOM is of great interest. Increases in organic C, which is a measure of SOM, have been reported by several workers (Waswa *et al*., 2007; Olubukola *et al*., 2010). Others have however observed a decline (Mucheru-Muna *et al*., 2014) or no significant effect (Opala *et al*., 2010) on SOM when tithonia was applied to soil. There was no clear effect of rate of tithonia application on SOM. Most of the studies that showed an increase in SOM used high rates (> 5 t ha^{-1}). The ability of an organic material to provide nutrients for crops and its ability to simultaneously increase the SOM are generally negatively correlated. High quality organic materials, e.g. tithonia, which are good for short-term soil fertility, because tithonia decomposes quickly, may therefore not necessarily maintain or build SOM (Delve and Ramisch, 2006) unless applied at unrealistically high rates.

Nutrient composition of tithonia

The reported nutrient content of tithonia is highly variable. High nutrients contents of 3.5 - 4.0% N, 0.35 - 0.38% P, 3.5 - 4.1% K, 0.59% Ca and 0.27% Mg have been reported (Jama *et al*., 2000). The high nutrient content in tithonia is credited to its ability to scavenge for nutrients in the soil due its proteoid root system. However, other studies such as Mucheru-Muna *et al*. (2007) reported much lower levels of N and P and suggest that there are other agroforestry species that have similar or higher levels of the major nutrients than tithonia (Table 2). Tithonia, just like other organic materials also contains substantial amounts of micronutrients (Reis *et al*., 2018) and is hence regarded as a complete fertilizer.

Table 2: Average nutrient composition (%) of organic materials applied in the soil from 2000 to 2003 in Meru South, Kenya.

Treatment	N (%)	P (%)	Ca (%)	Mg (%)	K (%)	Ash (%)
Cattle manure	1.4d	0.2a	1.0c	0.4b	1.8b	46.1a
Tithonia	3.0c	0.2a	2.2a	0.6a	2.9a	13.2b
Calliandra	3.3b	0.2a	0.9d	0.4b	1.1c	5.8 d
Leucaena	3.8a	0.2a	1.4b	0.4b	1.8b	8.7c

Means with same letter in each column, are not statistically different at p< 0.05. Source: (Mucheru-Muna *et al*., 2007).

Table 3: Effect of tithonia when applied alone or combined with MPR or TSP on maize yields.

Treatments	MGY t ha^{-1}	
	2001	2002
Control (-P)	1.34f	0.87e
Tithonia 2.5 t ha^{-1} (T2)	2.10bcde	1.5 d
Tithonia 5 t ha^{-1} (T5)	2.33abc	1.69cd
Tithonia 7.5 t ha^{-1} (T7)	2.29abcd	2.06bcd
MPR (P 80)	1.87e	2.21abc
TSP (P 80)	2.50a	1.81cd
MPR (P 40) + T2	2.36ab	2.30abc
MPR (P 40) + T5	2.34abc	2.31abc
MPR (P 40) + T7	2.36ab	2.7a
TSP (P 40) + T2	2.07cde	2.50a
TSP (P 40) + T5	2.29abcd	2.7 a
TSP (P 40) + T7	2.48a	2.84a
CV (%)	7.62	15.69

Means followed by the same letter in the same column are not significantly different P < 0.05 according to DMRT; MGY= Maize grain yield. MPR= Minjingu phosphate rock, TSP= Triple superphosphate. Source; Ikerra *et al.* (2006).

Response of crops to tithonia biomass

Initial studies on tithonia's ability to increase yields focused on maize, which is the staple food in most of sub-Saharan Africa. Tithonia was shown to be as effective as or better than inorganic fertilizers in Kenya (Kimetu *et al*., 2004; Opala *et al*., 2015), Zambia (Malama, 2001), Cameroon (Kaho *et al*., 2011) and Malawi (Ganunga *et al*., 2005). Table 3 shows typical results from Tanzania (Ikerra *et al*., 2006). Responses depended on the site and season. Later it was recommended that tithonia be tried on high value crops to increase financial returns and other crops were therefore studied. Tithonia induced higher yields of soybean and common beans than fertilizers in DR Congo (Emery *et al*., 2013) and Nigeria (Jorge-Mustonen *et al*., 2013) respectively. Tithonia also increased yields of vegetables such as Celosia in Nigeria (Babajide *et al*., 2012), rape in Zimbabwe (Chikuvire *et al*., 2013) and Kales in Kenya (Mwangi *and* Mathenge 2014). Yields of tomatoes increased by 130% with application of tithonia compared to the control with no nutrient inputs in Cameroon (Ngosong *et al*., 2015).

In Nigeria, the yield of okra was significantly higher in soil under tithonia fallow than under spear grass (Agbede *et al*., 2014). Tithonia also improved carrot yield and quality in Kenya (Jeptoo *et al*., 2013) and Nigeria (Agbede *et al*., 2017). The sweetness of watermelon was also enhanced under high levels of tithonia application (Aguyoh *et al*., 2004). Cassava (Kolawole *et al*., 2014) and yam (Agbede *et al*., 2014) yields in southwest Nigeria, sesame (Babajide *et al*, 2012) and pepper (Atta, 2011) have also been tested and found to positively respond to tithonia application.

The studies reviewed herein unequivocally demonstrated the agronomic effectiveness of tithonia. The better performance of tithonia compared to inorganic fertilizers was more pronounced in acid soils with high aluminum content compared to soils low in aluminum (Opala *et al*., 2012b). This was attributed to tithonia's ability to chelate Al and hence reduce aluminum toxicity (Opala *et al*., 2010). Tithonia's effectiveness was also related to its ability to reduce P sorption and increase P availability, provide a wide range of macro and micronutrients, improve soil structure and moisture conservation compared to inorganic fertilizers (Ikerra *et al*., 2006; Nziguheba *et al*., 2002; Adesodun *et al*., 2015).

Economics of tithonia use

The good agronomic performance of tithonia precipitated its rushed presentation to farmers although it had not been evaluated economically. Later, several studies combined agronomic evaluation with economic analysis. Nziguheba *et al*. (2002b) found greater financial returns when tithonia was applied alone than when fertilizers were used, or with tithonia integrated with fertilizers on maize in western Kenya. Conversely, others (Micheni *et al.* 2002; Mucheru-Muna *et al.* 2007) reported higher benefits when tithonia was integrated with fertilizers than when applied alone on maize in Central Kenya. The benefit-cost ratios (BCRs) for tithonia in the Mucheru-Muna *et al*. (2007) study were higher than the critical value of 2 (Table 4) which is the minimum required for adoption of a technology by farmers. There were however other treatments *e.g*. leaceania, calliandra and cattle manure in the same study which had higher BCRs and hence a better potential for adoption than tithonia. Micheni *et al*. (2002) ranked tithonia, when applied alone, above cattle manure in profitability but both were lower than inorganic fertilizers.

High labour costs and tithonia's unavailability in sufficient quantities when needed were however a major constraint in the utilization of tithonia biomass. Opala *et al*. (2010) observed that labor costs of tithonia accounted for 100% of the total costs in maize production in western Kenya when tithonia was applied alone and ranged from 69 to 87% of the total added costs when it was combined with inorganic

Table 4: Net benefit, benefit-cost ratio (BCR) and return to labor from 2000 to 2003 in Chuka, Meru South District, Kenya.

Treatment	USD ha^{-1}		
	Net benefit	BCR	Return to labor
Cattle manure	645b	5.0bc	5.0cb
Cattle manure+30 kg N ha^{-1}	616b	3.5c	6.8bc
Tithonia	784a	4.0bc	4.0d
Calliandra	653b	5.8ab	5.9cd
Leucaena	780a	7.0a	7.0bc
Tithonia+30 kg N ha^{-1}	787a	3.5c	6.3cd
Calliandra+30 kg N ha^{-1}	747a	4.4bc	9.0b
Leucaena+30 kg N ha^{-1}	572b	4.3bc	6.9bc
60 kg N ha^{-1}	666b	3. c	12.5a
Control	272c	5.2abc	5.2cd

Means with same letter in each column are not statistically different at p< 0.05. Source: Mucheru-Muna *et al.*, (2007).

Table 5: Net financial benefits (USD ha^{-1}) and benefit-cost ratio (BCR) at Bukura, western Kenya.

Treatment	First season		Second season		Third season	
	Net benefit	BCR	Net benefit	BCR	Net benefit	BCR
Control (no P)	-	-	-	-	-	-
Tithonia (20 kg P ha^{-1})	144	0.2	-351	-0.6	306	0.5
FYM (20 kg P ha^{-1})	323	3.3	130	1.3	379	3.4
MPR (60 kg Pha^{-1}) + urea	-51	-0.2	-188	-0.6	-196	-0.3
BPR (60 kg Pha^{-1}) + urea	-248	-0.9	-399	-1.5	-514	-0.9
TSP (60 kg Pha^{-1}) + urea	-228	-0.7	-284	-0.8	-512	-0.8
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	327	0.5	-232	-0.3	377	0.4
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	172	0.3	-506	-0.7	232	0.3
Tithonia (20 kg P ha^{-1}) + TSP(40 kg P ha^{-1})	405	0.5	-234	-0.3	711	0.8
FYM (20kgP ha^{-1}) + MPR (40 kg P ha^{-1})	223	1.2	25	-0.2	161	0.4
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	100	0.6	-95	-0.8	114	0.3
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	138	0.6	-10	-0.1	302	0.8

FYM: farmyard manure; TSP: triple superphosphate; MPR: Minjingu phosphate rock; BPR: Busumbu phosphate rock.
Source: Opala *et al.* (2010).

P sources. Consequently economic analyses showed negative financial returns on maize for many treatments. Where the returns were positive, the BCRs were too low (< 2) (Table 5) to motivate farmers to adopt the technology. In central Kenya**,** Mucheru-Muna *et al*. (2014) found that the treatments with inorganic fertilizers recorded the highest BCRs due to the low labour input required and that among the organic inputs tested, the sole manure treatment recorded higher returns compared to tithonia, Leucaena and Calliandra. Despite tithonia being used on the so-called high value crops to circumvent the low returns when used on maize, very few studies have conducted economic analyses on these crops. One study with tomatoes in Cameroon (Ngosong *et al*., 2015) however reported very high returns (8456 USD). The BCRs for this study were however not reported hence making it difficult to determine the potential for adoption of tithonia technology for tomato production.

Adoption of tithonia for soil fertility management

Among the earliest studies on adoption of tithonia technology was that by Makokha *et al*. (1999) who reported that only 52% of the farmers were using it in western Kenya. It was assumed that since these were initial years of the technology, the numbers would rise with time. However, this was not to be. For example, none of the farmers chose to test tithonia in western Kenya after focus group discussions but they instead chose farmyard manure integrated with fertilizers (Odendo *et al*., 2006). In an earlier study in the same region, Odendo *et al*. (2004) reported that except for those hosting the experiments, most farmers were unable to conceptualize how the tithonia biomass technology worked. In a similar study, Place *et al*. (2005) observed inside ICRAFS pilot villages, there was a rapid surge of users between 1997 and 1999, where the user rates reached about one quarter of households. There was then a significant decline in use in 2000. The explanation given for these trends was that considerable technical support along with the bandwagon effect may have led to early high rates of testing. This was followed by discontinuation by those who did not receive sufficient benefits or were unable to manage the technology after ICRAF and partners reduced backstopping efforts. Interestingly, Kiptot (2008) found that most farmers who experimented and rejected the technology claimed they did not notice any improvement in crop yields after using tithonia. This was however attributed to the fact that some farmers applied very small quantities of tithonia such as 1 t ha^{-1} instead of the recommended rate of 5 t ha^{-1} which in essence led to no noticeable effect on crop yield (Makokha *et al*.1999)

CONCLUSION

Two decades after tithonia was presented as a technology that would enhance food security and eradicate poverty in Africa, the situation has not changed despite enormous research and extension efforts to popularize the technology. A lot of useful biophysical information has been obtained from the research and its agronomic effectiveness repeatedly demonstrated. It is clear however that most of the perceived benefits associated with tithonia were in fact related to its being an organic material and therefore it was not unique as hyped by its earlier advocates. In several instances, some of the other organic materials and even fertilizers had better effects on soil properties, yields and economic returns than tithonia but these findings were often not given prominence. Instead tithonia was hastily presented to farmers before a thorough socioeconomic evaluation. The outcome was spectacular failure to adopt it by farmers because of high labor costs and negative financial benefits. Future research should therefore focus on integrated use of all available sources of nutrients on the farm in an environmentally and socioeconomically sustainable manner while involving farmers at all stages to ensure that only acceptable technologies are upscaled.

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