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Yield response of African leafy vegetables to combined manure and urea microdosing in West Africa

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Description of the subject. Fertilizers microdosing was tested for African leafy vegetables (ALVs) production to reduce the high rates of fertilizers usually applied to their production in West Africa.
Objectives. This study aims to (i) evaluate the response of three ALVs (*Amaranthus cruentus* L., *Solanum macrocarpon* L. and *Ocimum gratissimum* L.) to cattle manure combined with urea-N microdosing and application timing and (ii) assess their partial factor productivity.
Method. On-station trials were carried out over three growing seasons (2015 to 2017) in Northern Benin. Urea-N rates of 0, 10, 20, 30, 40 and 60 kg urea-N·ha^{-1} combined with 5 t·ha^{-1} of cattle manure (M5N0, M5N10, M5N20, M5N30, M5N40 and M5N60, respectively) and sole application as control (40 (M0N40) and 80 kg urea-N·ha^{-1} (M0N80)) and two urea-N application timings (T1 = 0 and T2 = 14 days after transplanting) were tested in a randomized complete block design with four replications.
Results. The M5N60 treatment resulted in the highest *A. cruentus* fresh yield and improved leaf yield by 90 and 151% compared to M5N0, and the average of the two no-manure input treatments M0N40 and M0N80, respectively, while M5N40 treatment improved *S. macrocarpon* fresh yield the best by 23% compared to M5N0. For *O. gratissimum*, no significant difference was found between urea-N microdose rates. Besides, urea fertilizer application timing affected neither fresh yields nor partial factor productivity for any studied ALVs species.
Conclusions. Reduced combination of urea-N and cattle manure is a promising nutrient management practice for ALVs production in West Africa as it improved yields while saving fertilizer for smallholder vegetable farmers.
Keywords. Fertilizer application, crop yield, yield factors, agricultural productivity, food security.

Réponse des légumes feuilles africains à l'apport combiné du fumier et d'urée en microdose en Afrique de l'Ouest
Description du sujet. La fertilisation microdose a été développée pour la production des légumes feuilles africains (LFA) afin de réduire les doses élevées de fertilisants souvent appliquées pour leur production en Afrique de l'Ouest.
Objectifs. Cette étude vise à (i) évaluer la réponse de trois légumes-feuilles africains (LFA, *Amaranthus cruentus* L., *Solanum macrocarpon* L. et *Ocimum gratissimum* L.) à l'apport combiné du fumier de bovins et d'urée en microdose puis (ii) évaluer leur facteur partiel de productivité de l'azote.
Méthode. Des expérimentations en station ont été conduites durant trois saisons culturales (2015 à 2017) au Nord Bénin. Six doses d'urée-N : 0, 10, 20, 30, 40 et 60 kg·ha^{-1} combinées à 5 t·ha^{-1} de fumier de bovins (M5N0, M5N10, M5N20, M5N30,

M5N40 et M5N60, respectivement) et l'application exclusive de 40 (M0N40) et 80 kg d'urée-N·ha^{-1} (M0N80) comme témoin et deux temps d'application de l'urée (T1 = 0 et T2 = 14 jours après le repiquage) ont été testés dans un dispositif en blocs aléatoires complets avec quatre répétitions.
Résultats. Le traitement M5N60 a enregistré le rendement en légume frais de *A. cruentus* le plus élevé, avec une amélioration de 90 et 151 % par rapport à M5N0 et les deux traitements M0N40 et M0N80, respectivement, tandis que le traitement M5N40 a amélioré le rendement frais de *S. macrocarpon* de 23 % par rapport à M5N0. Cependant, aucune différence significative n'a été observée entre les différentes doses d'urée-N appliquées sous *O. gratissimum*. De plus, la période d'application de l'engrais n'a affecté ni le rendement frais ni le facteur partiel de productivité d'aucune des espèces de légume étudiées.
Conclusions. Le microdosage combiné de fumier et d'urée constitue une pratique prometteuse de gestion des nutriments en Afrique de l'Ouest pour la production des LFA car elle permet d'améliorer les rendements tout en économisant les engrais pour les petits producteurs de légumes.
Mots-clés. Fertilisation, rendement des cultures, facteur de rendement, productivité agricole, sécurité alimentaire.

1. INTRODUCTION

The demand for African leafy vegetables (ALVs) is increasing for food diversification because of their crucial role in both food and nutrition security of rural populations (Olaniyi et al., 2008; Baruwa & Adesina, 2013). ALVs are vital income sources in urban and peri-urban areas (Diogo et al., 2010; James et al., 2010). They also constitute essential daily dietary components, including substantial iron, zinc, vitamins B, A and C contents, proteins, dietary fibres, and calorific values (Bamire & Oke, 2004; Afolayan & Jimoh, 2009; Ambrose-Oji, 2009). Despite the importance of ALVs, their production is yet limited to smallholder producers in Benin with low productivity (Sossa-Vihotogbe et al., 2013) due to low soil fertility and lack of appropriate management practices including fertilizer application, irrigation, pest and disease control (James et al., 2010; Leke et al., 2015). Moreover, there is limited information on nutrient recommendations for their production in various agroecosystems. However, the decline of soil fertility and associated crop yield decline is a critical issue for agriculture in sub-Saharan Africa (Saidou et al., 2012; Fonge et al., 2016). The practice of long-term traditional fallow has disappeared because of increased land pressure (Fermont et al., 2008). Various strategies were developed to improve soil fertility and increase crop yield. These strategies include organic amendments (cattle, poultry, and small ruminant) and mineral fertilizer application (Amidou et al., 2003; Tovihoudji et al., 2017b). The application of organic matter improves both physical (structural stability and porosity) and soil chemical properties through improved nutrient and water retention capacity (Harris, 2002; Bationo et al., 2007; Nakamura et al., 2011). Soil organic matter is also an essential source of bio-available nutrients for both plants and soil organisms (Harris, 2002; Mando et al., 2005; Zingore et al., 2007).

Despite its advantages, the adoption of organic fertilization is limited to small scale systems because of limited availability in a context where high rates are recommended to achieve sustainable crop production. Moreover, very high rates of manure application (> 40 t·ha^{-1}; Diogo et al., 2010, 2011) and mineral fertilizers (> 600 kg·ha^{-1}; Assogba-Komlan et al., 2007; Diogo et al., 2010) were reported in *Amaranthus cruentus* L. (AC) and *Solanum macrocarpon* L. (SM) production in Southern Benin. In Burkina Faso, rates up to 800 kg N·ha^{-1}, 140 kg P·ha^{-1} and 500 kg K·ha^{-1} were typically reported in vegetable production (Sangare et al., 2012). These application rates result in high production costs for smallholders and may decrease nutrient use efficiency. A study by James et al. (2010) reported that high levels of nitrogen delay the onset of flowering but improve leaf production. At the same time, various studies showed that high levels of inorganic fertilizers had detrimental environmental impacts (Wahocho et al., 2016; Sharma & Singhvi, 2017), including ground water and air pollution through nitrate leaching (Craswell, 2021), greenhouse gases emissions and nitrates accumulation in produced vegetables (Chowdhury & Das, 2015). Thus, to secure the year-round availability of high-quality vegetables improved nutrient management practices are needed through combined fertilizer application to preserve soil and vegetable health and address the spatio-temporal and input cost constraints.

Low-cost precision agriculture practices, such as fertilizer microdosing, are being promoted on cereals in sub-Saharan Africa as a viable alternative. Fertilizer microdosing consists of supplying a small amount of fertilizer at sowing or a few weeks (3 to 4) after emergence (Hayashi et al., 2008). Fertilizer microdosing has been extensively reported to improve cereals yields, nutrient use efficiency, profitability of small-scale agriculture and farmer income in sub-Saharan Africa (Niger, Burkina Faso, Mali, and Benin) (Camara et al., 2013; Ibrahim et al., 2015; Hayashi et al., 2008; Tovihoudji et al., 2017a). The integration of fertilizer microdosing in ALVs production would be a practical innovation for sustainable agriculture intensification in West Africa by optimizing the use of fertilizers and reducing both environmental impacts and health risks to vegetable consumers in the context of fertilizer scarcity in the region. Moreover, agronomic data on ALVs are scanty while they represent important sources of nutrient for human populations and income diversification for smallholder farmers in West Africa. This study is, to our knowledge, the very first one in West Africa on fertilizer microdosing application to ALVs. In this work, we aimed to:

– evaluate the response of three ALVs (*Amaranthus cruentus* L., *Solanum macrocarpon* L. and *Ocimum gratissimum* L.) to cattle manure combined with urea-N microdosing and application timing;
– assess partial factor productivity of applied nitrogen.

2. MATERIALS AND METHODS

2.1. Experimental site

On-station (dry and rainy seasons) trials were carried out at the Northern Research Center (CRA-Nord-Ina) of the National Agricultural Research Institute of Benin (INRAB), in Bembèrèkè municipality, Borgou Department (9.95 N, 2.72 E and 358 m. a.s.l.). The climate is of Sudanese type with a monomodal rainfall pattern from May to October. The average annual rainfall is 1,148 ± 212 mm (Tovihoudji et al., 2017b), and the highest rates occur in July and August. The average annual air temperature is 27.5 °C. The soil is classified as ferruginous tropical type according to the French soil classification system or Lixisols in the World Reference Base (Youssouf & Lawani, 2002; Tovihoudji et al., 2017a). The soil texture is sandy-loam (**Table 1**) with an average bulk density of 1.43 $g \cdot cm^{-3}$. The experimental field has been under peanut and sorghum production in single or in association with soybean for five years. Crop residues were left in the field but subjected to free cattle grazing. The soil is acidic, with low organic carbon and total nitrogen contents at 0-40 cm depth (**Table 1**).

2.2. Experimental design

Two trials were run for both *S. macrocarpon* and *O. gratissimum* from January to June 2016 (dry season) and from July 2016 to January 2017 (rainy season). Three trials were carried out on *A. cruentus*: in dry season (December 2015 to March 2016) and rainy season (May to July 2016 and August to October 2016) (**Figure 1**). A trial was considered as of a given season (dry or rainy) when at least its nursery, vegetative growth period and the first harvest fall in the dry or rainy season, respectively (**Figure 1**). All trials were carried out in a randomized complete block design with four replications. For all trials, two factors were evaluated:

– urea-N rate with five moderate levels in the dry season trial (0, 10, 20 and 30 kg urea-N·ha^{-1} combined with 5 t·ha^{-1} of cattle manure, refereed as M5N0, M5N10, M5N20 and M5N30, respectively) and sole application of 40 kg urea-N·ha^{-1}, named M0N40 as control;

Table 1. Soil and cattle manure physical and chemical characteristics before the experiments — *Caractéristiques physiques et chimiques du sol et du fumier de bovins avant les expérimentations.*

Parameters	**Soil depth (0-20 cm)**	**Soil depth (20-40 cm)**	**Cattle manure**
Soil texture			
Sand (%)	82.43	76.76	-
Silt (%)	3.77	9.04	-
Clay (%)	13.8	14.20	-
Texture	Sandy loam	-	
Soil chemical properties			
pH-H_2O	4.65	4.77	7.49
EC (μS)	173.4	142.6	1,780.50
Organic carbon ($g \cdot kg^{-1}$)	3.68	2.74	107.50
Total N ($g \cdot kg^{-1}$)	0.60	0.51	7.66
NH_4-N ($g \cdot kg^{-1}$)	0.008	0.004	0.021
NO_3-N ($g \cdot kg^{-1}$)	0.019	0.018	0.111
Total P ($g \cdot kg^{-1}$)	0.337	0.313	1.552
Available P ($g \cdot kg^{-1}$)	0.017	0.008	0.488
Total K ($g \cdot kg^{-1}$)	9	-	7

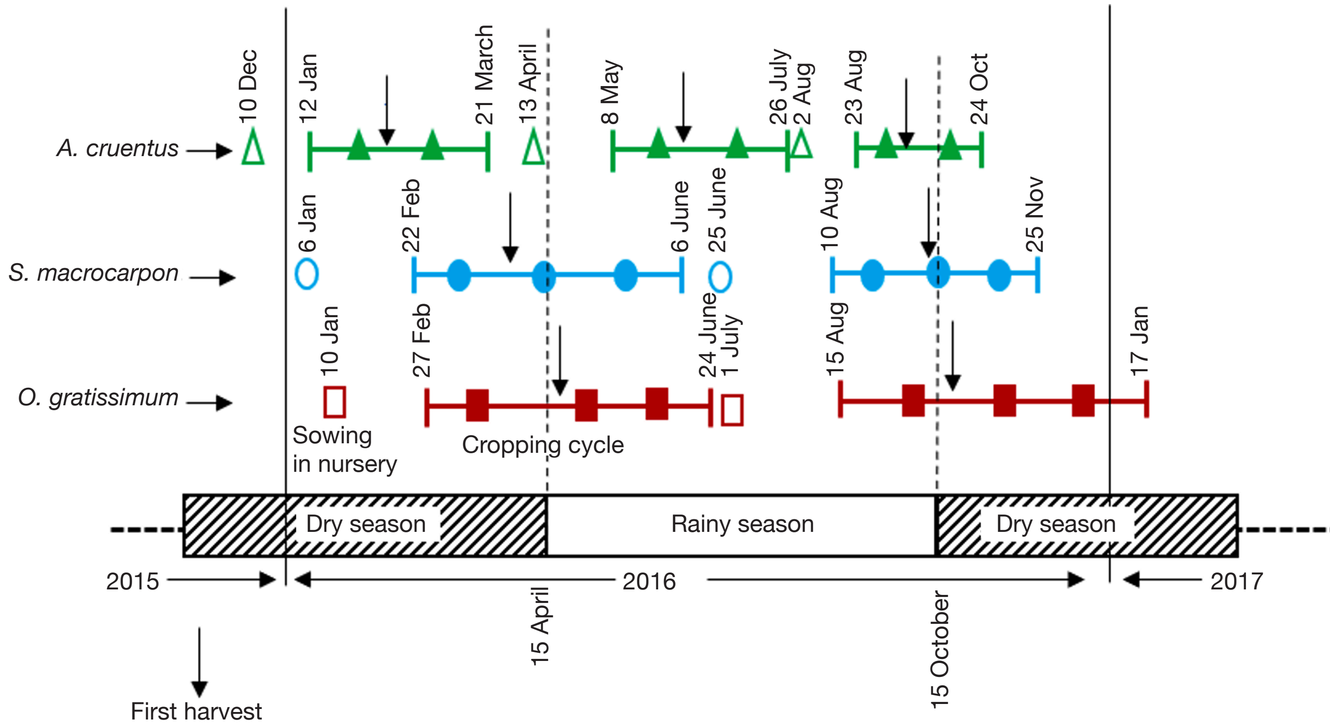


Figure 1. Timing of African leafy vegetables (ALVs) trials over the study period in Northern Benin — *Période de conduite des expérimentations sur les légumes feuilles africains (LFA) au Nord Bénin*.

– urea application timing with two levels (T1 = 0 and T2 = 14 days after transplanting).

As a little or no yield increase was found between the different nitrogen levels applied in the first trials, some treatments (M5N10, M5N30 and M0N40) were left out. We assumed that the increment of urea-N between treatments was probably not enough for a significant ALVs response. Therefore, three new fertilizer rates were added: M5N40 and M5N60 (40 and 60 kg urea-N·ha^{-1} combined with 5 t·ha^{-1} dry matter of cattle manure, respectively) and M0N80 (80 kg urea-N·ha^{-1} alone as control). The treatments considered for the second (and third) trial(s) were then M5N0, M5N20, M5N40, M5N60 and M0N80. Given the difference in crop cycle among vegetable species and irrigation requirements, ALVs species were installed independently following the same experimental design. Plots were 6 m^2 (6 m x 1 m) and separated by 1 m.

2.3. Fertilizer application and crop management

All plots (except M0N40 and M0N80) received 5 t·ha^{-1} of cattle manure (dry matter basis, DM) during soil preparation. This manure rate can be considered moderate as 30 to 40 t·ha^{-1} was reported to be applied by vegetable producers in the region (Assogba-Komlan et al., 2007; Oluoch et al., 2009). After manure collection from cattle corrals, a pile was made under a tree where it stayed for more than a month before application two weeks before transplanting. Urea (46% nitrogen) was mixed with water for uniform application. The leaves of the plants were rinsed with water afterwards. This fertilizer application method was shown to be more appropriate (time-saving, uniformity) compared to strip or hill applications (Adjogboto et al., 2019).

Seedlings were transplanted four weeks after sowing for *A. cruentus* and five to six weeks for *S. macrocarpon* and *O. gratissimum*. The latter two were transplanted at 30 cm x 30 cm, corresponding to a density of 11 plants·m^{-2}. In contrast, *A. cruentus* was transplanted at 20 x 20 cm, corresponding to a density of 25 plants·m^{-2}. During the dry season trial (January to June 2016), transplanting (by hand) was done on January 12th, 2016, for *A. cruentus* and February 22nd and 27th for *S. macrocarpon* and *O. gratissimum*, respectively. During the rainy season trial (August to December 2016), transplanting was done on August 10th, 15th and 23rd 2016 for *S. macrocarpon*, *O. gratissimum*, and *A. cruentus*, respectively (**Figure 1**). Weeding was manual and followed by hand hoeing to enhance water infiltration and avoid soil compaction.

Irrigation was ensured using a sprinkler system with an optimized water amount according to the Food and Agricultural Organization standards (Allen et al., 1998; FAO, 2009). An irrigation rate of 10 mm per day was split into two (morning and evening) during the dry season trials and dry spells falling within the rainy season trials. All plots received the same management practices until harvest except for fertilizer rates and application date.

2.4. Data collection

Vegetable yields. Staggered harvests of fresh leaves were made approximately at 4, 6, and 8 (*A. cruentus*), 6, 10, and 14 (*S. macrocarpon*) and 8, 12, and 16 (*O. gratissimum*) weeks after transplanting for each trial. Leaves were allowed to regrow after each harvest to enable sequential harvests (Materechera & Medupe, 2006). In the current study, three harvests were made for each vegetable species, following farmer practice although a higher number of harvests may be done for *O. gratissimum* if nutrients and water are available.

Partial Factor Productivity (PFP). Partial factor productivity (PFP) stands for an agronomic indicator used to assess crop yield response to each major applied nutrient (Akponikpe et al., 2008) and the short-term crop nutrient use efficiency under field conditions (Sangare et al., 2012). PFP of N was computed as the ratio of dry vegetable leaf yield to the total amount of N applied through cattle manure and urea (Cassman et al., 1998; Sangare et al., 2012). We computed this indicator for only nitrogen as the total applied amount of phosphorus and potassium did not differ among most treatments (M5N0, M5N10, M5N20, M5N30, M5N40 and M5N60).

2.5. Statistical analysis and modelling

Vegetable yields and partial factor productivity (PFP) of nitrogen were submitted to an analysis of variance under R.3.6.1 software (www.cran.r-project.org) using the aov model structure after data checking for normality and homogeneity of variance based on Shapiro-Wilk (Razali & Wah, 2011) and Levene (Pallmann et al., 2014) tests, respectively. A log transformation of the considered data (Akponikpe et al., 2008) was applied when data did not fit the normal distribution (*e.g.* yield of *A. cruentus*, PFP of *S. macrocarpon* and *O. gratissimum*). Significant differences in treatment means were separated using the Least Significant Difference (LSD) test at 5% probability error (Akponikpe et al., 2008). Pooled analysis of data (leaf yields and PFP) from the three (for *A. cruentus*) or two trials (for *S. macrocarpon* and *O. gratissimum*) was performed since interaction between year (cropping season) and treatment (urea-N microdosing) was not significant, except for *A. cruentus* (**Table 2**). Average leaf yield of each treatment appearing in each trial was presented. All studied factors (urea-N microdosing, urea application timing and season/year) were considered as fixed factors while replication was considered as a random factor in the model.

Table 2. Analysis of variance of *Amaranthus cruentus, Solanum macrocarpon* and *Ocimum gratissimum* yields affected by urea-N microdosing combined with cattle manure, application time and production season during 2015-2017 in Ina, Northern Benin — *Analyse de la variance des rendements de* Amaranthus cruentus, Solanum macrocarpon *et* Ocimum gratissimum *affectés par le microdosage d'urée-N combiné au fumier de bovins, le temps d'application et la saison de production au cours de la période de 2015-2017 à Ina, au Nord Bénin.*

	A. cruentus			***S. macrocarpon***			***O. gratissimum***	
	df	**F value**	**Pr (> F)**	**df**	**F value**	**Pr (> F)**	**F value**	**Pr (> F)**
Blocks	3	3.290	0.024	3	8.02	< 0.001***	8.17	< 0.001***
Season	2	11.881	< 0.001***	1	1.09	0.301 ns	275.06	< 0.001***
Rate	7	18.500	< 0.001***	7	2.87	0.012*	2.02	0.069 ns
Timing	1	0.004	0.948 ns	1	0.53	0.468 ns	2.53	0.117 ns
Season x Rate	5	3.370	0.008**	1	1.34	0.253 ns	0.48	0.493 ns
Season x Timing	2	0.447	0.641 ns	1	0.72	0.400 ns	1.81	0.184 ns
Rate x Timing	7	0.202	0.984 ns	7	0.11	0.998 ns	0.754	0.627 ns
Residual	92			58				

df: degree of freedom — *degré de liberté*; F value: Fisher statistic value — *valeur de la statistique de Fisher*; Pr (> F): probability of significance — *probabilité de signification*; ns: not significant — *différence non significative;* *, ***: probability significant at 0.05 and 0.001, respectively — *probabilité de signification à 0,05 et 0,001, respectivement*; season — *saison*: dry and rainy seasons — *saisons sèche et pluvieuse*; Timing: 0 and 14 days after transplanting — *0 et 14 jours après repiquage*; Rate: 0, 10, 20, 30, 40 and 60 kg urea-N·ha^{-1} combined with 5 t·ha^{-1} of cattle manure, 40 and 80 kg urea-N·ha^{-1} without manure — *0, 10, 20, 30, 40 et 60 kg urée-N·ha^{-1} combinés avec 5 t·ha^{-1} de fumier de bovins, 40 and 80 kg urée-N·ha^{-1} sans fumier.*

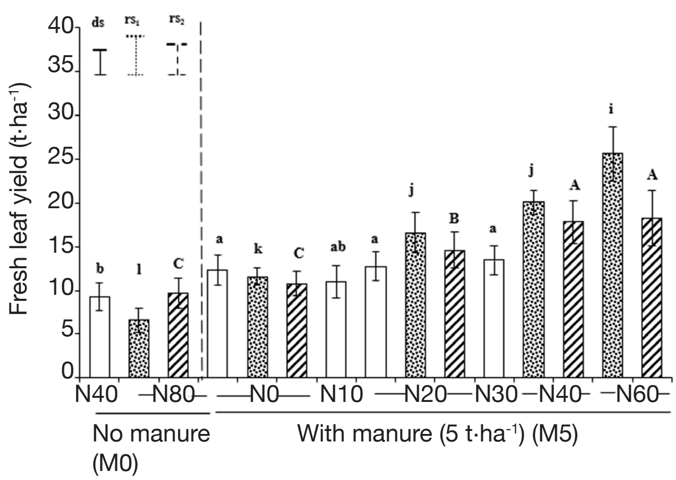
Quadratic regression analysis was performed to model the leaf yield response of the studied ALVs to N application (Akponikpè et al., 2011). We cumulated the amount of nitrogen provided by both applied manure and urea, as the total applied nitrogen.

3. RESULTS

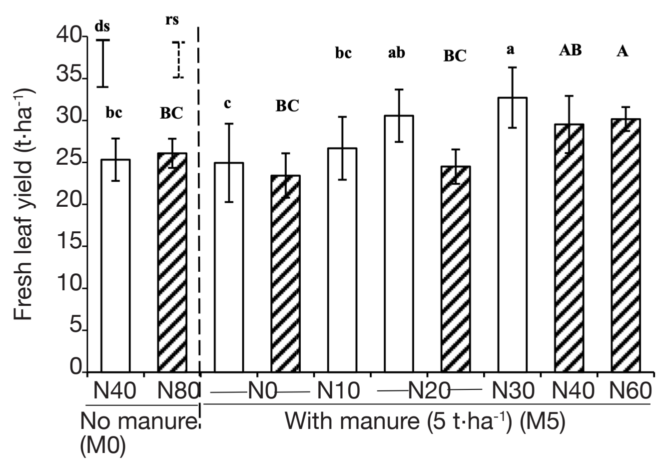
3.1. Fresh vegetable yield

For *A. cruentus* (three trials) and *S. macrocarpon* (two trials), a significant effect of urea-N microdosing was found on fresh yield ($p < 0.05$; **Table 2**) contrarily to *O. gratissimum* (two trials) ($p > 0.05$; **Table 2**). Meanwhile, little or no significant yield was observed above M5N40 for *S. macrocarpon* (**Figures 2b**). For *A. cruentus*, an application of 60 kg N·ha^{-1} combined with cattle manure (M5N60) resulted in the highest yield and produced on average 10.35 (90%) and 13.19 t·ha^{-1} (151%) of fresh matter more than M5N0 and the two treatments M0N40 and M0N80 (on average 8.71 ± 3.29 t·ha^{-1}; with 14% dry matter) (**Figure 2a**). However, moderate (M0N40) or high rate (M0N80) of urea-N application alone on *A. cruentus* achieved the lowest fresh yield compared to the other rates (**Figure 2a**). For *S. macrocarpon*, the application of 40 and 60 kg urea-N·ha^{-1} combined with 5 t·ha^{-1} of cattle manure resulted in similar fresh vegetable yield (29.85 ± 4.83 t·ha^{-1}; with 16% dry matter) and moderately improved fresh yield by 23% compared to the control without mineral fertilizer (M5N0,

a. *A. cruentus*



b. *S. macrocarpon*



c. *O. gratissimum*

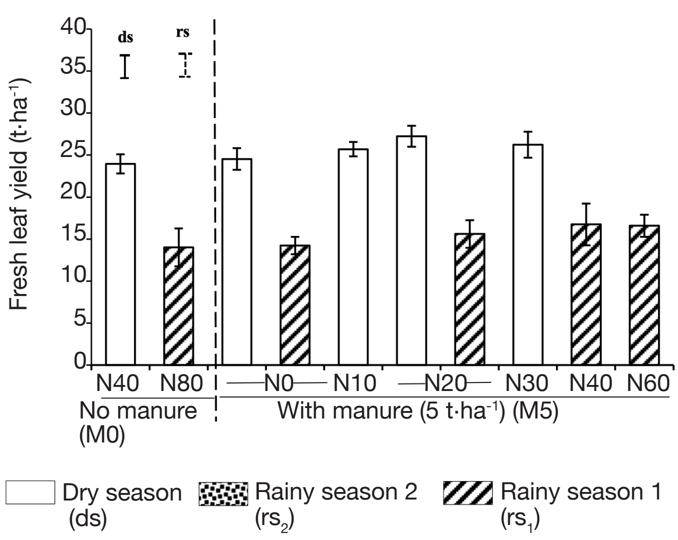


Figure 2. Effect of combined cattle manure and urea-N fertilizer microdosing application on *Amaranthus cruentus* (**a**), *Solanum macrocarpon* (**b**) and *Ocimum gratissimum* (**c**) fresh vegetable yields during 2015-2017 at Ina, Northern Benin — *Effet de l'application combinée de fumier de bovins et du microdosage d'urée-N sur les rendements en légumes frais de* Amaranthus cruentus *(**a**),* Solanum macrocarpon *(**b**) et* Ocimum gratissimum *(**c**) au cours de la période 2015-2017 à Ina, au Nord Bénin.*

M_xN_y stands for x t·ha^{-1} of cattle manure combined with y kg urea-N·ha^{-1}. Error bars on the histograms denote the standard deviation of the mean. Isolated error bars represent the least significant difference between means of the same season at $p < 0.05$. Treatments with the same letter of the same character did not significantly differ at 0.05 probability error — *M_xN_y signifie x t·ha^{-1} de fumier de bovins combiné à y kg d'urée-N·ha^{-1}. Les barres d'erreur sur les histogrammes indiquent l'écart-type de la moyenne. Les barres d'erreur isolées représentent la valeur de la plus petite différence significative (PPDS) entre les moyennes de la même saison à* p < 0,05. *Les traitements ayant la même lettre de même caractère ne diffèrent pas significativement à une probabilité d'erreur de 0,05.*

Figure 2b). For *O. gratissimum* in both seasons, all microdose rates gave on average 20.51 (± 3.95) t·ha-1 of fresh leaf yield (with 16% dry matter, **Figure 2c**).

The production season significantly affected *A. cruentus* yields ($p =$ 0.000; **Table 2**) and *O. gratissimum* ($p < 0.001$; **Table 2**) contrarily to *S. macrocarpon* ($p > 0.05$; **Table 2**). Yields recorded in the rainy season were higher than in the dry season for *A. cruentus* as opposed to *O. gratissimum* (**Figures 2a** and **2c**). A significant interaction was found between the production season and the urea fertilizer rate for *A. cruentus* ($p = 0.008$; **Table 2**).

Besides, fertilizer application timing did not affect fresh yields for any studied vegetable species ($p > 0.05$; **Table 2**).

3.2. Partial factor productivity of N

Both urea-N rate and production season significantly affected the partial factor productivity of N for all studied vegetables ($p = 0.001$; **Table 3**). Overall, partial factor productivity decreased slightly with urea-N application rates when combined with cattle manure. Applied nutrients were more N-productive during the dry season compared to the rainy one. Over both production seasons, the best partial factor productivity was found under the half-recommended urea-N sole application rate on *S. macrocarpon* (100.04 ± 22.92 kg DM·kg^{-1} N; **Figure 3b**) and *O. gratissimum* (105.97 ± 15.99 kg DM·kg^{-1} N; **Figure 2c**). But no clear trend was observed for *A. cruentus*.

Besides, both fertilizer application timing resulted in similar PFP for all studied ALVs species ($p > 0.05$; **Table 3**).

3.3. Modelling leaf yield response to nitrogen application

Relatively good coefficients of determination (R^2) were found with quadratic Yield-N models for the studied vegetable species although not significant. It was of 51% for *A. cruentus* ($p = 0.170$), 49% for *S. macrocarpon* ($p = 0.185$) and 43% for *O. gratissimum* ($p = 0.242$; **Figure 4**).

4. DISCUSSION

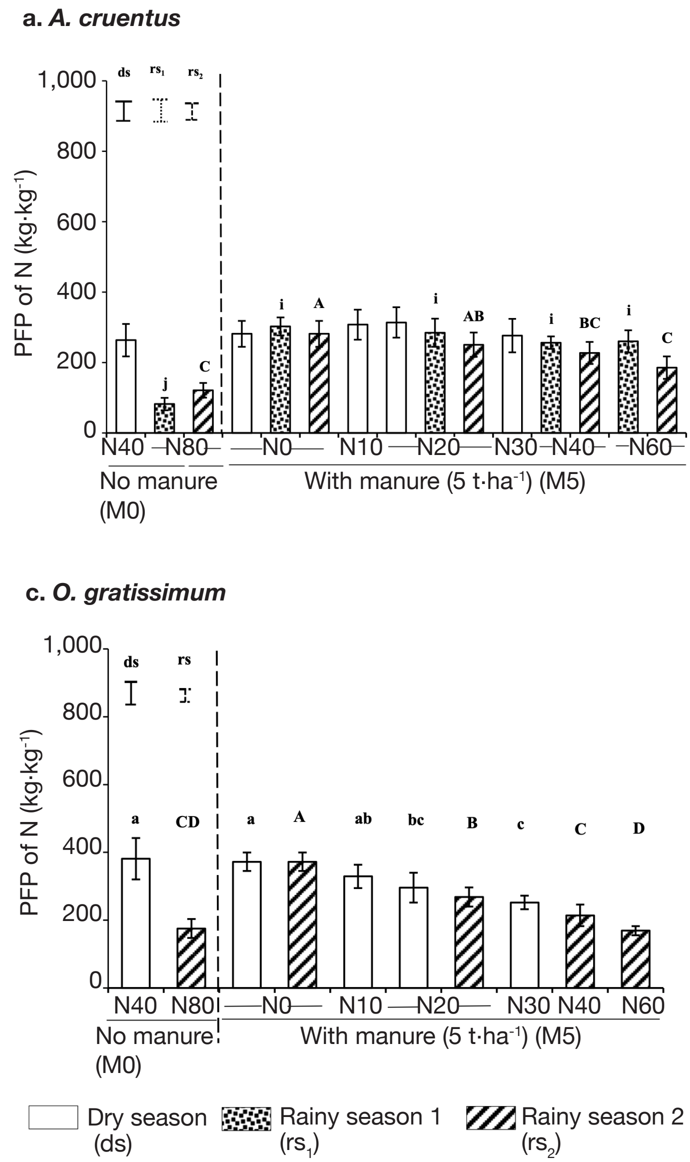
4.1. Response of vegetable species to urea-N microdosing combined with cattle manure application

The significant fresh vegetable yield improvement of *A. cruentus* and *S. macrocarpon* of nitrogen microdosing application up to 40 kg N·ha^{-1} combined with 5 t·ha^{-1} dry matter of cattle manure (**Tables 2** and **3**, **Figures 2** and **3**), could be attributed to the synergistic effect of the combination of manure ((38.3 kg N·ha^{-1}, 7.76 kg P·ha^{-1} and 35 kg K·ha^{-1}) and urea-N, allowing better nutrient availability for plant growth. In the sole urea-N treatment, given the low soil pH (4.65) NH_4 nitrification to nitrate may further increase soil acidity and reduce P and K solubilization impeding plant growth. In the combined application treatments, there might be a slight liming effect of the manure (pH =7.49) compensating pH decrease from nitrification. However, increased nitrogen rate was reported to enhance nitrate availability to plants (Assogba-Komlan et al., 2007). Olaniyi et al. (2008) reported that *Amaranthus* spp. fresh and dry shoot

Table 3. Analysis of variance of partial productivity factors of *Amaranthus cruentus, Solanum macrocarpon* and *Ocimum gratissimum* affected by microdosing of urea-N combined with cattle manure, application time and production season during 2015-2017 in Ina, Northern Benin — *Analyse de la variance des facteurs partiels de productivité de* Amaranthus cruentus*,* Solanum macrocarpon *et* Ocimum gratissimum *affectés par le microdosage d'urée-N combiné au fumier de bovins, le temps d'application et la saison de production au cours de la période 2015-2017 à Ina, au Nord Bénin.*

	A. cruentus			*S. macrocarpon*			*O. gratissimum*	
	df	**F value**	**Pr(> F)**	**df**	**F value**	**Pr (> F)**	**F value**	**Pr (> F)**
Blocks	3	14.080	< 0.001***	3	8.81	< 0.001***	2.917	0.042*
Season	2	16.185	< 0.001***	1	24.47	< 0.001***	419.24	< 0.001***
Rate	7	13.794	< 0.001***	7	13.12	< 0.001***	19.24	< 0.001***
Timing	1	0.010	0.922ns	1	0.00	0.972ns	2.43	0.124ns
Season x Rate	5	1.919	0.099ns	1	2.99	0.089ns	0.04	0.842ns
Season x Timing	2	0.687	0.506ns	1	0.24	0.623ns	1.47	0.230ns
Rate x Timing	7	0.453	0.866ns	7	0.66	0.704ns	0.50	0.828ns
Residual	92			58				

df, F value, Pr (> F), ns, *, ***, Season, Timing, Rate: see **table 2** — *voir **tableau 2***.



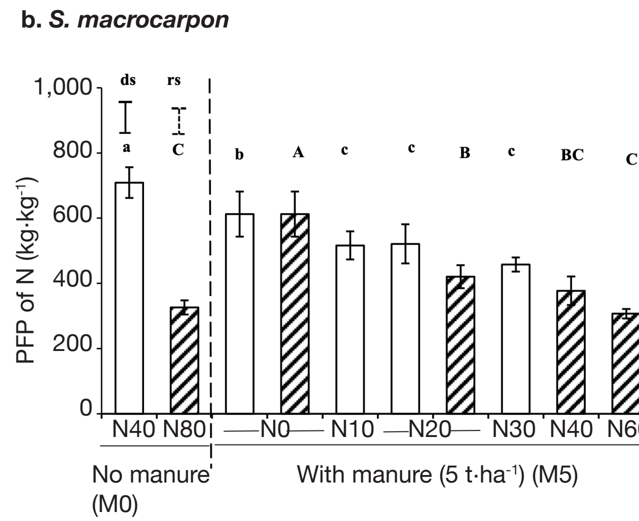


Figure 3. Effect of combined cattle manure and urea-N fertilizer microdosing application on *Amaranthus cruentus* (**a**), *Solanum macrocarpon* (**b**) and *Ocimum gratissimum* (**c**) partial factor productivity (PFP) of N during 2015-2017 at Ina, Northern Benin — *Effet de l'application intégrée de fumier de bovins et du microdosage d'urée-N sur le facteur partiel de productivité de* Amaranthus cruentus *(**a**),* Solanum macrocarpon *(**b**) et* Ocimum gratissimum *(**c**) au cours de la période 2015-2017 à Ina, au Nord Bénin.*

MxNy, error bars, isolated error bars, letters — *MxNy, barres d'erreur, barres d'erreur isolées, lettres*: see **figure 2** — *voir **figure 2**.*

yields increased under nitrogen supply rate up to 45 kg N·ha^{-1} in Nigeria. Still, no significant difference was recorded above (up to 60 kg N·ha^{-1}). Similarly, Akanbi & Togun (2002) noticed a yield increase to nitrogen application rate combined with cattle manure application up to 30 kg N·ha^{-1} but no significant yield difference was found between 30 and 60 kg N·ha^{-1} on an Alfisol soil type in Nigeria.

However, the lack of yield response to urea-N application although combined with manure for *O. gratissimum* contrarily to *A. cruentus* and *S. macrocarpon* (**Table 2**, **Figure 2**) may be explained by the physiology of the plants, the difference in nutrient requirements of each vegetable species and the perennial characteristic of *Ocimum* (Awah, 2010; Kpadonou et al., 2012). *Ocimum* has deeper roots and a potential development as a shrub allowing more nutrient uptake from deep soil layers and laterally. Our results agreed with the findings of Golcz et al. (2006), who reported no significant difference between various high nitrogen rates (150; 200 and 250 kg N·ha^{-1}) of various *Ocimum basilicum* L. cultivars in India. However, early studies have shown a positive response to nitrogen application at high nitrogen rates up to 250 kg N·ha^{-1} on *Ocimum basilicum* L. For instance, Biesiada & Kuś (2010) found the highest biomass yields at 150-250 kg N·ha^{-1}. Similarly, Bufalo et al. (2015) observed higher fresh yield per plant under organic fertilization at 150 kg N·ha^{-1} rate and conventional fertilizers at 250 kg N·ha^{-1} compared to 250 kg N·ha^{-1} and 150 kg N·ha^{-1} of organic fertilization and conventional fertilization, respectively.

Lower *A. cruentus* fresh yield achieved by the sole moderate or high urea-N rate application compared to the M5N0 treatment (**Figure 2**) pointed out the benefits from organic nutrient source and its combination with

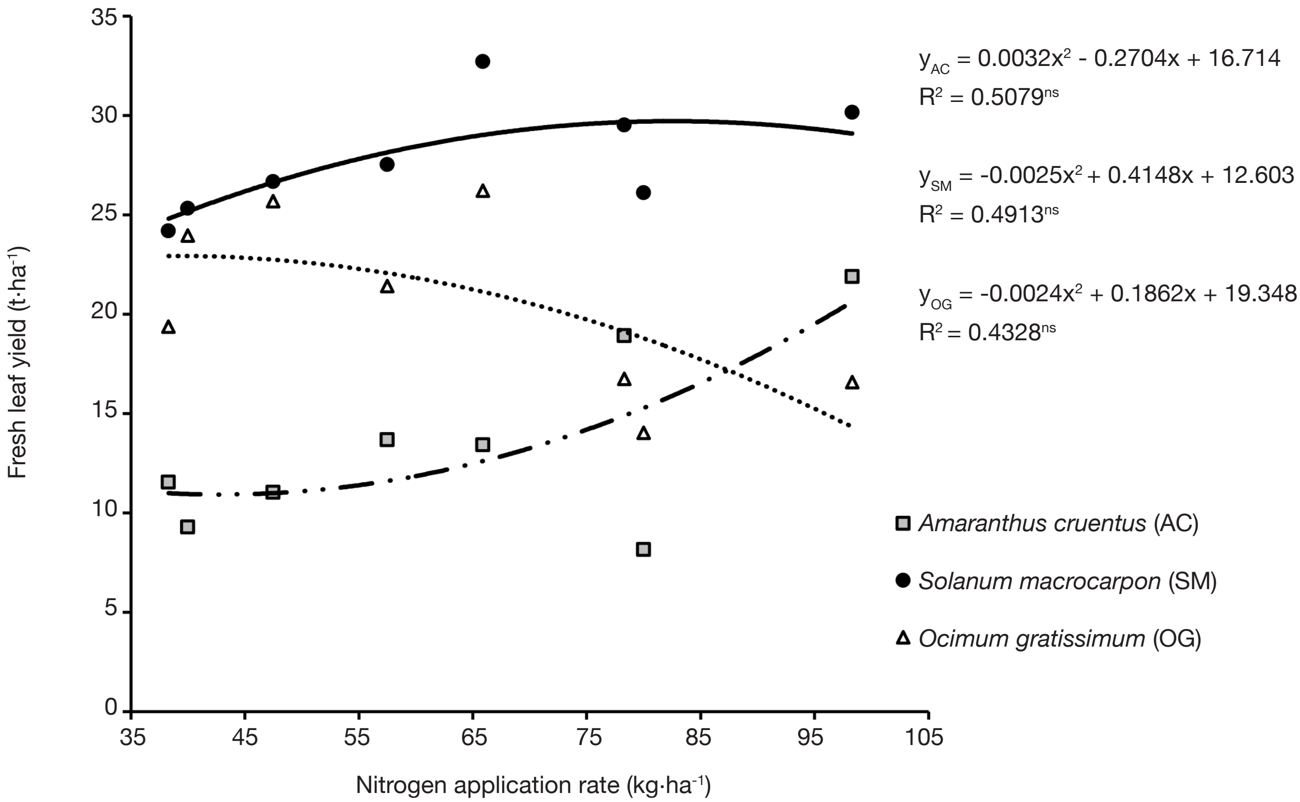


Figure 4. Leaf yield response of *Amaranthus cruentus* (AC), *Solanum macrocarpon* (SM) and *Ocimum gratissimum* (OG) to total N fertilizer application from combined cattle manure and urea-N microdosing — *Réponse de* Amaranthus cruentus *(AC),* Solanum macrocarpon *(SM) et* Ocimum gratissimum *(OG) à l'application d'azote provenant de la combinaison du microdosage de fumier de bovins et d'urée-N*.

The measured yields (points) are averages of the treatments modelled by the parabolic curves — *les rendements mesurés (points) sont les moyennes des traitements modélisés par les courbes paraboliques*; ns: not significant at 0.05 — *non significatif à 0,05*.

mineral fertilizer for sustainable production. Improved biomass yield recorded under the combined urea application with cattle manure treatments (M5N10-60) compared to urea alone (M0N40 or M0N80) could be attributed to its ability to slowly release the required nutrients. Moreover, the combined urea and manure has a relatively higher content in macro (38.3 kg N·ha^{-1}, 7.76 kg P·ha^{-1} and 35 kg K·ha^{-1}) and micronutrients compared with the sole urea-N treatments. Moreover, organic matter supply contributes to soil physical, biological and chemical properties enhancement resulting in increased soil water holding capacity (Harris, 2002; Nakamura et al., 2011; Iren et al., 2016). In contrast, the urea application is characterized by a quick-release, providing nitrogen to the plant at the initial growth stage (Makinde et al., 2015). Therefore, at higher rates, substantial mineral N losses through leaching may occur likely in the rainy season (Zhang et al., 2017). Moreover, this lower performance of urea alone could also be attributed to other factors (sandy soil with low organic carbon content) (**Table 1**).

4.2. Effect of timing of fertilizer application on vegetable yields

The early timing of the urea-N application gave equal performance compared to the two weeks after transplanting one (**Table 2**), allowing farmers to delay fertilizer supply up to 14 days after transplanting. As all concerned plots received cattle manure at plot preparation, plants of the late mineral fertilizer application plots, benefited from nutrients released from cattle manure mineralization before urea application (Adjogboto et al., 2019). This allowed them to catch up with the earlier ones during the growth stage. This result is in agreement with Kalinowski et al. (1992). They reported no significant difference between grain amaranth yields for fertilizer application before planting and at plant thinning in Peru. Nonetheless, early fertilizer application would be highly recommended to stimulate young transplanted plant growth through rapid root development and nutrient uptake, significant advantages of the fertilizer microdosing technology.

4.3. Effect of urea-N application combined with manure on partial factor productivity

Increased application of urea with cattle manure did not increase nitrogen productivity. However, fresh vegetable yields were significantly improved compared to the control without inorganic fertilizer (**Figure 3**). This trend could probably be attributed to mineral N losses through leaching and gas emissions (Olaniyan et al., 2006; Sangare et al., 2012) since partial factor productivity of N variation was more remarkable in the rainy season trial. Sangare et al. (2012) reported lower partial factor productivity of N of lettuce and attributed it to higher inputs supply in the production at Kodeni (Burkina Faso), leading to nutrients losses, especially N gaseous loss.

Besides, the significant difference of vegetable yields and N partial factor productivity of studied vegetable species between seasons could be explained by better nutrients and water management in the dry season trial. During this season, water application was controlled by supplying plant requirements which might allow better water and nutrients use. Also, crop evapotranspiration during the trials was higher during the dry season with significant yield improvement (Likpètè et al., 2019).

4.4. Towards recommendation on the combining cattle manure with reduced mineral fertilizer in ALV productions systems

The highest yield was found with 60 (*A. cruentus*), 40 (*S. macrocarpon*) and 20 (*O. gratissimum*) kg urea-N·ha^{-1} when combined with 5 t·ha^{-1} of cattle manure. Higher nitrogen rates were reported earlier in vegetable production in the West African vegetable production systems. Tongos (2016) reported nitrogen rate up to 120 kg N·ha^{-1} as the optimal rate required for maximum growth of *A. cruentus* in Northern Guinea Savannah zone of Nigeria, whereas Ojo & Olufolaji (1997) found 80 kg NPK·ha^{-1} as the optimal NPK fertilizer rate required for *S. macrocarpon* production in Ibadan, Nigeria producing 15.2 t·ha^{-1} of the fresh shoot after evaluation of four increasing fertilizer rates: 0, 40, 80 and 120 kg NPK·ha^{-1}. These results suggested that fertilizer rates usually applied to vegetable production could substantially be reduced without yield reduction. Lower mineral fertilizer rates recorded in the current study compared to previous studies could be attributed to the effect of organic matter and the appropriate fertilizer application timing, allowing better nutrient uptake by plants for growth and biomass accumulation. These results have earlier been demonstrated in cereal crop production under microdose fertilization technology in West Africa (Ibrahim et al., 2015; Tovihoudji et al., 2017a).

However, results obtained in this study for *O. gratissimum* could be considered as a starting point of information provision on nutrient management for this species as a leafy vegetable in West Africa. This species could be produced with a low nitrogen rate (20-40 kg urea-N·ha^{-1}) combined with manure (5 t·ha^{-1} of cattle manure, dry basis). The existing literature is mostly relative to essential oil production, nutritional and medicinal properties of leaves and herbal yields, often evaluated at only one harvest at plant maturity, not staggered harvests as in the current study (Kéita et al., 2000; Agarwal & Varma, 2014; Irondi et al., 2016).

Based on these results, fertilizer microdosing combined with cattle manure can successfully be applied to ALVs production without compromising vegetable yield allowing reduction in manure rate of about seven times compared to more than 40 t·ha^{-1} and mineral fertilizer about six times compared to more than 600 kg·ha^{-1} of mineral fertilizers as reported by Assogba-Komlan et al. (2007).

5. CONCLUSIONS

Amaranthus cruentus and *S. macrocarpon* responded positively to urea-N microdosing application up to 40 kg N·ha^{-1} when combined to 5 t·ha^{-1} dry matter of cattle manure application contrarily to *O. gratissimum*. However, partial factor productivity decreased slightly with urea-N application. Urea fertilizer microdosing combined with moderate cattle manure could successfully be applied to ALVs production, allowing to save production cost and therefore improve farmers' income. Furthermore, its large-scale adoption would be an alternative to reduce the human health risk of vegetable consumption, often due to high rates of fertilizer residual effect on the one hand and environmental pollution on the other. Moreover, the integration of this technology into farmers management practices could be a promising strategy to increase the production of ALVs allowing an all-time availability, a pathway to combat unbalanced diet for poor farmers. Further studies are needed to assess the long-term effect and the economic benefits of fertilizer microdosing application to ALVs in different locations in West Africa.

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Abbreviations

AC: *Amaranthus cruentus* L.
ALV: African Leafy Vegetables
CIFSRF: Canadian International Food Security Research Fund
Df: Degree of Freedom
IDRC: International Development Research Centre
INRAB: National Agricultural Research Institute of Benin
LFA: Légumes Feuilles Africains
LSD: Least Significant Difference
OG: *Ocimum gratissimum* L.
PFP: Partial Factor Productivity
PPDS: Plus Petite Différence Significative
SM: *Solanum macrocarpon* L.

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