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Optimization of plant density and fertilizer application to improve biofortified common bean (*Phaseolus vulgaris* L.) yield on Nitisols of South-Kivu, Eastern D.R. Congo

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ABSTRACT

Soil nutrient depletion and poor farming practices are serious challenges limiting crop productivity in soils of the eastern Democratic Republic of Congo (D.R. Congo). An experiment was conducted in two cropping seasons to assess the effect of plant density (25 plants m^2 and 33 plants m^2) and fertilizer application (with and without NPK) on the yield and yield components of three biofortified common bean varieties (HM21-7, RWR2245 and RWR2154). The experiment involved two plant densities, two fertilizer rates and three varieties arranged in a split-split plot design with three replications. Results showed that yield significantly varied with plant density, variety and fertilizer rate ($p < 0.05$). The best performing variety in terms of grain yield was HM21-7 (1.5 t ha^{-1}) as compared to RWR2154 (1.09 t ha^{-1}) and RWR2245 (1.14 t ha^{-1}). The NPK fertilizer increased the grain yield by 38.2%. Grain yield increased also with the plant density, highest grain yield being recorded on higher plant density (1.37 t ha^{-1}) as compared to low lower plant density (1.25 t ha^{-1}). Agronomic efficiency (AE) was influenced by the variety, with the highest AE obtained on RWR2245 (23.27 kg kg^{-1}) and on high plant density (20.34 kg kg^{-1}). Therefore, we concluded that increasing the plant density by reducing the plant spacing, using NPK fertilizer and high yielding varieties provide with an opportunity to improving common bean yields on Nitisols dominating the highlands of eastern D.R. Congo.

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1. Introduction

Common beans (*Phaseolus vulgaris* L.) are one of the main staple crops worldwide and in Africa, particularly [1,2]. According to FAO [3], Africa is the third common bean producer (21.3% of the world production) after Asia (43.9%) and America (32.2%). Democratic Republic of Congo (D.R. Congo) is the ninth African country in terms of tonnage of common bean produced (172 833.03 tons) after Tanzania (844 024.59 tons), Uganda (651 385.08 tons) and Kenya (499 624.56 tons) who are the first three bean producers in Africa [3]. Common bean is widely cultivated across all cropping systems (monoculture and/or intercropping), commonly associated with cereals and/or perennial crops and contributes to significantly improve soil fertility [4,5].

Common bean production in DR Congo is challenged by significantly low yields of ~0.6 t ha^{-1} [6]. These low yields of common bean are due to many factors such as inadequate farmer practices, low soil fertility, lack of high yielding varieties, and high pressures of disease and insect pests [7]. Many scholars recommended different planting density and fertilizer use as a means for improving crop yield by smallholder farmers [1,8]. Thus, increasing plant density and using fertilizer could be promising practices to fill the yield gap in common bean cultivation.

According to Mushagalusa et al. [1], South-Kivu's bean farmers sow beans in bulk (with no particular plant spacing) and some plant it at 40 cm × 20 cm spacing (making 25 plants m^2) with no fertilizer application though there are soil nutrient depletion conditions. Determining the optimal plant density for common beans can be challenging because it depends on factors such as the variety, local environmental conditions, and crop management practices [4]. High plant densities can result in overcrowding, increased competition for resources, and reduced airflow, which can increase disease pressure and reduce the overall yield [9]. On the other hand, very low plant density can result in underutilization of available soil resources and reduced yield potential. Finding the right balance requires careful consideration of local conditions and plant growth and development monitoring [10,11].

However, optimizing common bean yield will require application of fertilizer to compensate crop demand depending on the availability of soil nutrients that is limiting in many tropical soils with a low soil fertility level attributed to natural and anthropic factors [4]. Thus, the knowledge of soil type and characteristics is important for their management for crop growth and yield [9].

Ferralsols and nitisols are the dominant soil groups in agricultural areas of eastern DR Congo [7,8,12]. They are acidic soils with low cation exchange capacity (CEC), low base saturation and high phosphorus fixation due to high concentrations of aluminum and iron oxides [13]. These toxicities can inhibit the growth and activity of nitrogen-fixing bacteria, reducing the ability of common beans to fix nitrogen effectively [14]. In addition, poor soil fertility is one of the major constraints limiting nutrient availability on depleted soils due to overuse and soil erosion [15,16]. This situation is very limiting for the growth and development of crops such as common beans. These highly weathered soils are also characterized by low nutrient availability, including nitrogen, soil organic carbon and

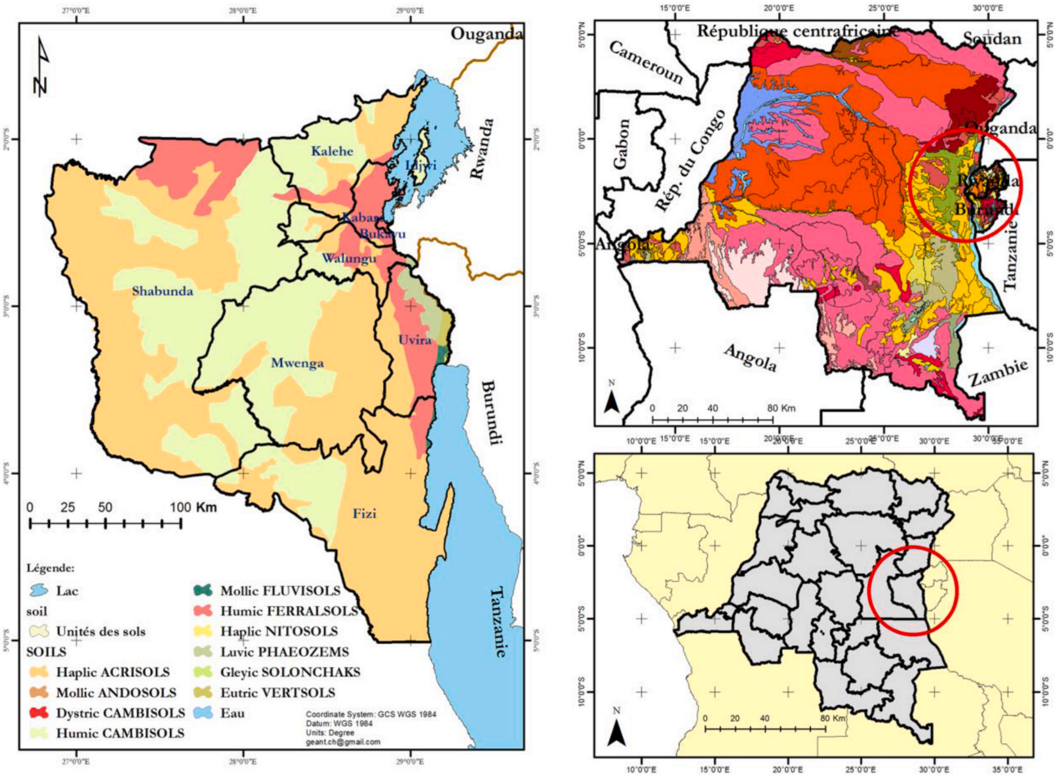

Fig. 1. South-Kivu soil map and location of Kabare territory, eastern DR Congo. The soil classification was made based on the WRB classification [8]).

nutrients required for nitrogen-fixing bacteria to thrive and effectively fix nitrogen [8,17]. This can limit nitrogen availability for legume growth, which relies on starter nitrogen to promote symbiotic fixation. Managing soil fertility through proper nutrient management practices is essential to maintaining optimal soil fertility levels for sustainable bean production [18]. Despite the nutrient deficiencies, the soils have good physical properties, such as the agglomerated polyhedral structure, which allow for proper tillage and thus contribute to the success of sustainable low-input agriculture [14,19].

The objectives of this study were (i) to assess the effect of plant density and fertilizer application on the yield components of three biofortified common bean varieties and (ii) to assess the agronomic efficiency of the fertilizer application on selected varieties.

2. Materials and methods

2.1. Study area

Experimental trials were established at the Mulungu station of the National Institute for Agronomic Studies and Research (INERA) (02° 19′ 09.2″S, 028° 47′ 06.9″E, and at 1752 m above the sea level), in Kabare territory, eastern DR Congo (Fig. 1). The soil of the study area belongs to the Nitisols class according to the World Reference Base (WRB) Soil taxonomy. This soil is developed on volcanic rocks and is characterized by a high clay activity and organic matter (OM) content, a large mineral reserve, and is moderately acidic (Table 1).

According to the weather conditions, Mulungu station has a humid tropical climate of type *Aw*3 according to the Koppen-Geiger climatic classification. It is characterized by two alternating seasons: the rainy season (September to May) and the dry season (June to August). Data from the INERA-Mulungu meteorological station showed an average annual rainfall of 1730 mm and an average temperature of 22.83 °C in 2017, 2018 and 2019 (Fig. 2). Fig. 1 presents the spatial distribution of South-Kivu soils. In fact, soil of South-Kivu is mainly dominated in the following order by Acrisol > Cambisol > Ferralsols. In addition, the soil group such as Nitisols are present in Kabare where this experiment was conducted.

2.2. Experimental design and trial management

The trial was designed as a factorial design with three factors: plant spacing with two levels (E1: 40 cm × 20 cm and E2: 30 cm × 20 cm), variety with three levels (HM21-7, RWR2245 and RWR2154) and NPK application with two levels (with NPK and without NPK). The whole experimental field was divided into three blocks (replications) separated by a 2 m row. Each block consisted of 12 plots (treatments) spaced 0.5 m apart (50 cm). The surface area of each plot was 12.96 m^2, i.e. 3.6 m long and 3.6 m wide. Sowing was done in rows with two seeds per hole, i.e., 25 plants per m^2 (250 000 plants ha^{-1}) for E1 and 33 plants per m^2 (333 333 plants ha^{-1}) for E2. The plots with the first sowing density consisted of 9 rows of 18 plants each, i.e. 162 plants per plot. The plots with the second sowing density consisted of 12 sowing rows with 18 plants each, i.e. 216 plants per plot. The total area was 720 m^2, 48.7 m long and 14.8 m wide. The soil was fertilized with NPK (17-17-17) at a rate of 150 kg ha^{-1}. Weeding was done twice, the first time at pre-flowering (30 days after sowing) and the second time at pod filling (60 days after sowing).

The common bean varieties used in this study were bush genotypes bred by the International Centre for Tropical Agriculture (CIAT)-HarvestPlus project. The seed color of the varieties ′HM21-7′ and ′RWR2245′ is red, while that of the variety ′RWR2154′ is white. HM21-7 has the largest seeds, while RWR2245 and RWR2154 have medium-sized seeds. All the three varieties mature between 80 and 90 days after sowing and their yield potential ranges from 0.8 to 1.5 t ha^{-1} for "HM21", from 0.8 to 1.0 t ha^{-1} for RWR2245 and from 0.8 to 1.4 t ha^{-1} for RWR2154. The recommended area for better growth is that of an altitude varying between 1000 and 1800 m. a.s.l.

Yield parameters were measured during the experimental period. Total biomass (BM) was measured at 50% of pod formation and weighed using a precision balance. The number of pods per plant (NPP) was counted manually at 50% pod formation on 15 plants randomly selected from each plot. The number of seeds per pod (NSP) at harvest (95 days after sowing) was obtained by manually counting the seeds contained in 15 pods randomly selected from the plot and then weighing one hundred (100) seeds with a precision

Table 1
Soil characteristics of the study site, Mulungu in eastern D.R. Congo.

Soil depth (cm)	0–10	10–20	20–30	>30	Average	Rating	References
pH H_20	5.2	5.2	4.7	4.7	4.95	Strongly acidic	[23]
N (%)	0.37	0.27	0.34	0.27	0.31	Low	[24]
C (%)	2.36	1.89	0.90	0.48	1.41	Medium	[24]
Ca (Cmol/kg)	5.90	6.13	5.73	5.66	5.9	Medium	[25]
Mg (Cmol/kg)	2.40	2.73	2.15	2.20	2.37	High	[24]
K (Cmol/kg)	0.20	0.14	0.10	0.11	1.14	Medium	[24]
CEC (meq/100g)	21	17	15	12	16.25	High	[26]
Total P (mg kg^{-1})	35	30	22	22	27.25	Very high	[27]
Sand (%)	14	8	8	6	9	–	–
Clay (%)	62	64	70	80	69	–	–
Silt (%)	24	27	22	14	21.75	–	–
Textural class	Clayey	Clayey	Clayey	Clayey	Clayey	–	–

CEC: Cation exchange capacity

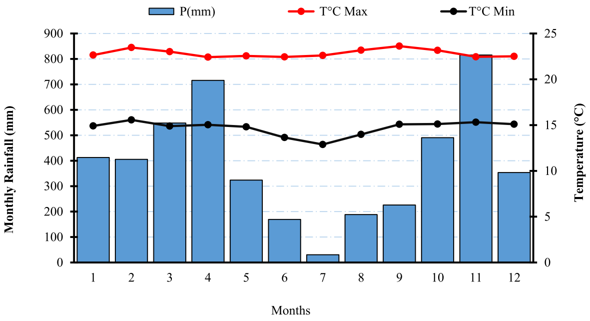

Fig. 2. Rainfall and temperature distributions (2017, 2018, and 2019) at the study site.

balance to obtain the weight of 100 seeds in grams (W100G). The plot yield in g m^2 at harvest was obtained by weighing the seeds obtained in each plot and then expressed in t ha^{-1} after extrapolation using least common multiple method. The harvest index (HI) in percent (%) was obtained by multiplying the ratio of the plot yield to the total biomass by 100.

2.3. Soil samples collection and analysis

Soil samples were collected from the experimental site at 5 depths (0–10 cm, 10–20 cm, 20–30 cm, and >30 cm) using an auger and physico-chemical properties were analyzed following the standard procedures. All samples were bulked and composited and a 1 kg composite sample was taken for analyzing physical and chemical properties of the soil according to Legesse et al. [20]. Physico-chemical properties such as soil pH, organic carbon (OC), total N, available P, exchangeable bases (Ca, Mg and K), CEC and texture (particle size distribution) were analyzed. Soil pH was measured with pH-meter; the total N content of the soil was determined by the procedure of the Kjeldahl method, soil OC was determined following the method of Walkley and Black. Available P and S and exchangeable basic cations were determined using the Mehlich-III multi-nutrient extraction method. The CEC was determined by using the 1 N ammonium acetate (pH 7) method. Particle size analysis was done by the hydrometer method according to Abdu et al. [21].

2.4. Calculation of the agronomic efficiency

Agronomic efficiency (AE) is a measure of the effectiveness with which plants utilize applied nutrients for growth and production. It is commonly calculated as the ratio of crop yield to the amount of nutrient applied. The AE was calculated using the following equation. $EA = (Y1–Y2)/FQ$ where Y1: is the seed yield obtained by fertilizer application; Y2: Yield obtained without fertilizer and FQ: is the quantity of fertilizer applied per hectare [22]. A higher agronomic efficiency value indicates that the crop used the applied nutrient more effectively to produce a higher yield, while a lower value indicates that the nutrient was not used efficiently. It indicates that for each kilogram of nutrient applied, the crop produced a certain number of kilograms of grain yield.

2.5. Statistical data analysis

Data collected was coded using Microsoft Excel 2016 and analysis was performed using R 4.2.0 software. The Shapiro-Wilk test was used to test for normality. Restricted maximum likelihood (REML) mixed model analysis was used to assess statistical differences among treatments. Plant spacing, NPK application and varieties were considered as fixed effects and seasons and replications as random effects. Models were tested using the Akaike Information Criterion (AIC). The model with the lowest AIC value was selected. Thus, the interaction effect model (spacing × NPK × variety) was selected for growth parameters, yield and agronomic efficiency. When the effects of the treatments were statistically significant, the post hoc range test with standard error of the difference (SED) was used to determine how the treatments differed from each other at an alpha level of 0.05. Separation of means was performed with Tukey's HSD Test under REML conditions.

3. Results

3.1. Physico-chemical properties of the study area soils

Results presented in Table 1 showed that the soil of the experimental site is strongly acidic ($pH < 5.5$), low in nitrogen (0.31%), medium content of OC (1.41%), Ca (5.9 Cmol kg^{-1}) and K (1.14 Cmol kg^{-1}). In addition, Mg (2.37 Cmol kg^{-1}) and CEC (16.25 meq/ 100 g) are high while total P is very high (27.25 mg kg^{-1}).

3.2. Analysis of yield components of selected common bean varieties under different plant spacing and NPK fertilizer application

3.2.1. Effect of seasonality on common bean growth and yield parameters

Results in Table 2 show that the season significantly influenced common bean biomass and harvest index ($p < 0.01$), with the highest biomass recorded in the 2017 growing season (3.7 kg per plot) compared to the 2018 season (2.3 kg per plot), while harvest index was higher in the 2018 season compared to the 2017 season. No seasonality difference was observed for the number of pods per plant, the number of seeds per pod and 100 seed weight and the grain yield ($p > 0.05$).

3.2.2. Effect of plant spacing on the common bean growth and yield parameters

Results presented in Table 2 show that biomass, grain yield and harvest index varied with plant spacing ($p < 0.05$) while the number of pods per plant, the number of seeds per pod and 100 seed weight were not affected by the plant spacing. The plant spacing of 40 cm × 20 cm had the highest biomass (3.16 kg per plot) compared to the plant spacing of 30 cm × 20 cm (2.87 kg per plot). Grain yield also varied significantly with plant spacing ($p < 0.05$), with higher yield recorded when planted at 30 cm × 20 cm (1.37 t ha^{-1}) compared to 40 cm × 20 cm (1.25 t ha^{-1}). The same trend was observed for the harvest index; higher HI observed on the spacing of 30 cm × 20 cm (0.64) compared to the common bean planted under 40 cm × 20 cm (0.57).

3.2.3. Effect of varieties on the common bean growth and yield parameters

Results showed that plant biomass, the number of pods per plant, 100 seed weight, grain yield and the harvest index varied significantly ($p < 0.05$) with common bean varieties that did not influence significantly ($p > 0.05$) the number of seeds per pod (Table 2). Among the varieties, HM21-7 had the highest plant biomass (3.61 kg per plot), the highest number of pods per plant (7.57), the highest 100 seed weight (40.10 g), and highest seed yield (1.5 t ha^{-1}). However, it had lowest harvest index (0.56) compared to RWR2154 and RWR2245.

3.2.4. Effect of fertilizer application on the common bean growth and yield parameters

The plant biomass, the number of pods per plant, the number of seeds per pod, 100 seed weight, and grain yield were significantly affected by NPK fertilizer application ($p < 0.05$), except the harvest index that showed no significant effect ($p > 0.05$). The highest plant biomass (3.33 kg per plot), the highest number of pods per plant (7.65), the highest number of seeds per pod (3.93), the highest 100 seed weight (39.76 g) and the highest grain yield (1.52 t ha^{-1}) were obtained when 150 kg ha^{-1} NPK was applied compared to the control ploy without NPK (Table 2).

3.2.5. Effect of the interaction between fertilizer application and variety on common bean grain yield

Results in Fig. 3 show that the grain yield was highly significantly affected by the fertilizer application and variety interaction across both seasons (Table 2). Highest grain yield was obtained on HM21-7 under 150 kg ha^{-1} fertilizer (1.71 t ha^{-1}) while lowest grain yield was on RWR2245 without NPK fertilizer (0.90 t ha^{-1}).

3.3. Agronomic efficiency of NPK application on common bean yields under nitisols

Results from this experiment (Fig. 4) showed that agronomic efficiency did not vary with the season ($p < 0.05$). However, it varied

Table 2

Yield components of three common bean varieties under two plant spacing and NPK fertilizer across two cropping seasons.

Study factors	BM (kg)	NPP	NSP	P100G (g)	Yield (t ha^{-1})	HI (%)
Plant spacing						
E1 (40 cm × 20 cm)	3.16 ± 1.17a	6.84 ± 1.43a	3.63 ± 0.48a	38.94 ± 1.51a	1.25 ± 0.30a	57.88 ± 22.86a
E2 (30 m × 20 cm)	2.87 ± 0.81b	7.17 ± 1.32a	3.84 ± 0.48a	39.36 ± 1.38a	1.37 ± 0.41b	64.03 ± 15.86b
Variety						
HM21-7	3.61 ± 0.96a	7.57 ± 1.06a	3.85 ± 0.57a	40.10 ± 1.55a	1.50 ± 0.29a	56.73 ± 14.15a
RWR2154	2.73 ± 0.74b	6.69 ± 1.45b	3.73 ± 0.44a	38.52 ± 1.37b	1.23 ± 0.34b	62.83 ± 22.04a
RWR2245	2.71 ± 1.06b	6.76 ± 1.46b	3.63 ± 0.43a	38.83 ± 0.88b	1.19 ± 0.40b	63.30 ± 22.22a
Fertilizer application						
- NPK	2.70 ± 0.96a	6.36 ± 1.22a	3.55 ± 0.46a	38.54 ± 1.38a	1.10 ± 0.29a	58.89 ± 20.46a
+NPK	3.33 ± 0.96b	7.65 ± 1.22b	3.93 ± 0.44b	39.76 ± 1.27b	1.52 ± 0.32b	63.02 ± 19.14a
Prob. Season	*<0.01***	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*<0.01***
Prob. Spacing	*<0.05**	*>0.05*	*>0.05*	*>0.05*	*<0.05**	*<0.05**
Prob. Variety	*<0.01***	*<0.05**	*>0.05*	*<0.01***	*<0.01***	*<0.05**
Prob. Fertilizer	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*<0.01***	*>0.05*
Prob. Spacing × Variety	*>0.05*	*<0.05**	*>0.05*	*>0.05*	*>0.05*	*>0.05*
Prob. Spacing × Fertilizer	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*>0.05*
Prob. Variety × Fertilizer	*>0.05*	*>0.05*	*<0.05**	*>0.05*	*<0.05**	*>0.05*
Prob. Spacing × Variety × Fertilizer	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*>0.05*
CV (%)	12.3	15.3	10.1	2.5	16.1	15.2

Legend: NPP: number of pods per plant, NSP = number of seeds per pod, W100G = weight of 100 grains, BM = biomass, HI = Harvest Index, Prob. = Probability; CV = Coefficient of variation.

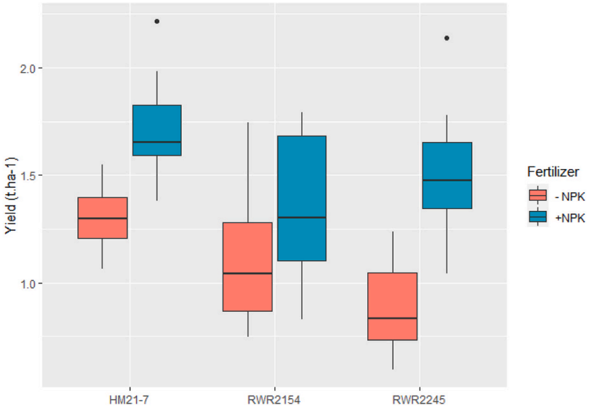

Fig. 3. Yield variation with the interaction between the variety and NPK fertilizer application.

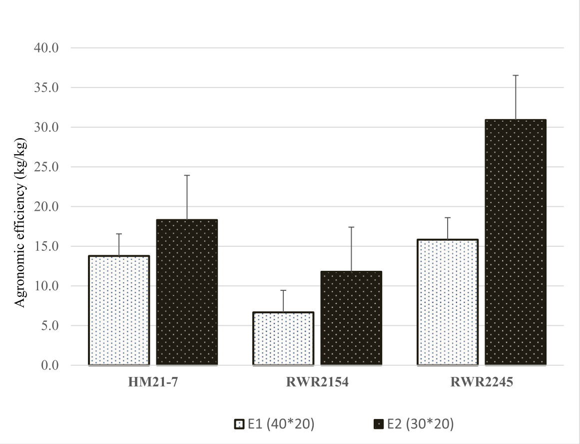

Fig. 4. Agronomic efficiency variation under different varieties and plant spacing.

significantly with plant spacing and variety ($p < 0.05$). In contrast to yield, the agronomic efficiency was highest on RWR2245 (23.37 kg kg^{-1}) compared to the other two varieties. Highest agronomic efficiency was obtained on the spacing of 30 cm × 20 cm (20.34 kg kg^{-1}).

4. Discussion

4.1. Physico-chemical properties of the soil in the study area

The particle size distribution of the study area was in the following order: Clay > Silt > Sand, with clay-textured soil. In fact, the soil of this study area was strongly acidic (pH < 5.5) [23]. According to IUSS Working Group WRB [13], acidic soil may be caused by human activities (e.g. continuous use of ammonium fertilizer, low input of organic material, etc.), degraded soil mineral by crops due to underutilization, etc. In general, the application of limestone and/or organic matter (e.g. compost and farmyard manure, green manure) is a recommended agricultural strategy to acidic soil [1,23,28,29]. In addition, soil acidity significantly limits crop growth and highly acidic soil limits the availability of important micro and macronutrients mainly phosphorus, while increasing the solubility of cations that limit plant growth such heavy metals (Mn and Al) [21,25]. Thus, livestock play an important role as a manure source in improving soil fertility level in the context of crop and livestock integrated system [30,31].

Soil N and OC are low in the study area (Table 1) [24]. Nitrogen is one of the principal soil nutrient affecting growth, development and crop yield in many tropical soils worldwide. Lower levels of N and OC in the soil decrease significantly crop yields. This lower content is generally due to poor agricultural practices, increased rate of mineralization, and lack of organic amendments [21]. Nitisol of the study area is non-deficient in P, with values > 15 mg kg^{-1} (Table 1). Application of 150 kg ha^{-1} of NPK fertilizer increased common bean yields from 1.1 to 1.5 t ha^{-1} (Table 2). Available phosphorus in soils is an essential nutrient for various metabolic fonctions (e.g. photosynthesis) [28]. External application of Phosphorus affects significantly a positive response of common bean yield and their components as well as the number of pods per plant. According several scholars [8,32,33], optimal application rate of P play an important role in the nodulation activity of common bean and other grain legumes such soybean and peas. Exchangeable K was medium (1.14 Cmol kg^{-1}) in our experimental field (Table 1) [24]. Tropical soils are generally deficient in K. Continuous cropping may deplete the soil K reserves under smallholder farming conditions [18].

4.2. *Varietal response on common bean yield and its components*

Number of pods per plant and the grain yield varied significantly with common bean genotypes used across both growing seasons (Table 2). The highest grain yield across both seasons was obtained with the HM21-7(Table 2). This result is in agreement with the findings reported on Faba bean by Ref. [11], by Refs. [5,34] on common bean. Several studies on the common bean yield due to varietal performance reported that the difference of grain yield is attributes to many factors including the genetic performance, environmental adaptation, and the resistance to biotic and abiotic stresses [34,35]. The highest common bean yield was obtained with HM21-7 (1.6 t ha^{-1}) while RWR2245 and RWR2154 varieties had 1.2 and 1.3 t ha^{-1}, respectively (Table 2). According to Ref. [36] and ref. [34], differences in growth habit and morphology among the genotypes may be responsible for differences in yield performance. In agreement with this study, ref. [37] and ref. [38], who reported significant differences of grain yield among varietal performance. According to Refs. [39,40], yield response is significantly affected by varietal resistance to environment stress and environment adaptability.

4.3. *Fertilizer application on the yield and its components of common bean variety*

NPK fertilizer application significantly affected common bean yield and its components (Table 2). Highest yield and its components were obtained when selected common bean varieties were sown under fertilized plots. These results are in agreement with previous studies on common bean [1,4,7,9,14,41,42] and other grain legumes such as soybean [16] and peas [8]. In general, common bean responds positively to the application of N and P fertilizer. In our case, grain yield increased from 1100 kg ha^{-1} to 1600 kg ha^{-1} when 150 kg ha^{-1} of NPK fertilizer was applied. This result is in agreement with ref. [28] who reported that nitrogen and phosphorus fertilization significantly increase growth, yield and yield components in N and P-deficient soils.

According to Ref. [8], applying N and P improves nodulation parameters and consequently affected the growth and yield of grain legumes. In fact, common bean has a little tolerance to low soil fertility level such as Nitisols and Ferralsol [28]. Thus, previous studies on common bean recommended nitrogen fertilizer up 100 kg ha^{-1} for optimizing grain yield in degraded soils [43–45]. This finding is in agreement with ref. [28], who reported that optimum nitrogen fertilizer dose had a significant effect on pod filling, number of seeds per plant, and grain yields when soils is deficient in major nutrients. This result agreed with ref. [46] who revealed that the varietal response of common bean to fertilizer application is attributed to availability of nutrients that enhance crops physiology and productivity in degraded soil.

4.4. *Plant density effect on the yield and its components on selected common bean varieties*

The number of seeds per pod and the grain yield was highly significantly affected by plant density (Table 2). Increased plant density from to 25 to 33 plants m^2 allowed increasing common bean grain yields on Nitisols of Kabare. These results are in agreement with those obtained on common bean by Ref. [1] on Ferralsols in Kabare. According to Ref. [47], increase of common bean grain yield due to increased plant density can be attributed to the grown of sub-branches at the lower part of the plant. In addition, a determination of the life history stages of early flowering and pod formation is a crucial for maximizing grain yield. Results of ref. [48] demonstrated that increasing plant density from 22 to 33 plants m^2 allowed increasing the mean grain yield from 821.4 to 928 kg ha^{-1}. Many studies showed that higher plant density decreases the grain yield per unit due to intraspecific competition (for light, water, and nutrients) and by the diseases intensity it favors [5,8]. According to Ref. [48], increase of grain yield due to increased plant density is the result of the sum of seed weight yield per plant.

Common bean grain yield was highly affected by the plant density (Table 2) with higher yields obtained on high plant density, and is consequently the optimum plant density. Results of ref. [49] who tested six plant densities on the cowpea and those of ref. [4] who tested three plant densities (20, 25, and 33 plants per m^2) on the common bean found that the grain yields increase proportionally with the plant density. This result is also in agreement with refs. [50,51] who reported that increasing plant density is associated with higher common bean yields. The highest bean yield under high plant density could be attributed to individual adaptability (for water stress, nutrients, and nutrients) of varietal genotypes. In addition, the major factor influencing optimal plant density for any particular condition is the variety. Thus, the effect of plant density on growth and yield attributes in common bean could vary due to varietal features as well [52].

4.5. *Agronomic efficiency of fertilizer application under selected common bean varieties*

Fertilizer application improves plant growth and development for better yields. The highest fertilizer agronomic efficiency was obtained by the RWR2154 variety (23.37 kg kg^{-1}) when sown on high plant density (20.34 kg kg^{-1}) (Fig. 4). According to Ref. [8], the agronomic efficiency of fertilizer application depends on farming practices such as optimal plant density, use of performing varieties and others practices. In agreement with our case, ref. [53] revealed that the nutrient use efficiency of common bean varieties depends significantly on the capability for each varieties to use available soil nutrients effectively. On the other hand, the AE is high for variety requiring low levels of practice (such a low-input agriculture) with minimum use of N fertilizers, thus cutting production costs and reducing environmental damage [53]. Under better soil characteristics (e.g. sufficient soil moisture and nutrients), plant population is necessary to utilize all the available resources and thus affects consequently nutrient use effectiveness [54]. Generally, AE varied significantly according to cropping season, fertilizer rates and timing of application, as well as by the interaction season and fertilizer rate [55]. In addition, ref. [16] showed that, the EA is also affected by the fertilizer type, their results showing significant differences in AE between Urea and DAP (Diammonium phosphate) on soybean in Kabare (eastern DR Congo). In addition, the AE of fertilizer obtained by Ref. [1] on common bean and by Ref. [8] on peas show that the AE varies with DAP rates in Kabare. Thus, the knowledge of nutrient uptake and use efficiency is important for supply of essential nutrients to crop in adequate amount and proportion [56].

5. Conclusion

This on-farm experiment assessed the effect on grain yields of the plant density and NPK fertilizer rate using three selected common bean varieties. Practicing the appropriate plant density and fertilizer rate showed potential in increasing grain yields of high yielding varieties. Application of 150 kg ha^{-1} of NPK increased common bean yield from 1.1 to 1.6 t ha^{-1} as well as high plant density (1.3–1.4 t ha^{-1}). In addition, grain yield was affected by the varietal performance. For instance, HM21-7 (1.6 t ha^{-1}) and RWR2254 (1.3 t ha^{-1}) performed better at higher plant density compared to RWR2154 (1.2 t ha^{-1}). Providing much reliable recommendations is difficult from two short rainy seasons (2017–2018) within a single location. We, therefore, recommend for multilocation experiments, more varieties and plant densities, different fertilizer types and doses to provide strong recommendations to farmers before calling for adoption of the treatments tested in the current study.

Author contribution statement

Patient M. Zamukulu, Dieumerci R. Masumbuko and Espoir M. Bagula: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; and wrote the paper.

Jean M. Mondo: Analyzed and interpreted the data and wrote the paper.

Francine B. Safina, Thierry H. Cishesa, Géant B. Chuma and Anicet B. Kavange: Performed the experiments; analyzed and interpreted the data; and wrote the paper.

Dieumerci R. Masumbuko: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; and wrote the paper.

Josué W. Kazadi: Performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Gustave N. Mushagalusa: Conceived and designed the experiments; contributed reagents, materials, analysis tools or data; and wrote the paper.

Antoine K. Lubobo: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; and wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

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

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