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Breeding runner bean for short-day adaptation, grain yield, and disease resistance in eastern Africa

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Abstract

Runner bean (*Phaseolus coccineus* L.), also known as butter bean in Kenya, is a high value vegetable and grain crop traditionally grown in high altitudes (>1,800 m) of eastern Africa for domestic consumption and processing. However, it has not received attention from breeders. Consequently, farmers rely on low-yielding landraces which are susceptible to diseases. Available long-day vegetable type varieties are poorly adapted to tropical conditions. In 2005, a regional program was initiated at the University of Nairobi to develop tropically adapted short-day varieties with better agronomic potential to meet both producer and consumer requirements. The objective of this study was to determine the agronomic potential of advanced grain-type runner bean lines selected from populations derived from crosses between local landraces and long-day European varieties. Fifty lines were selected from 139 $F_{6.8}$ lines based on their previous performance at Kabete Field Station and Ol Joro Orok in 2012 and 2013. The 50 lines were evaluated at both sites during the 2014 long rain season. The best 20 lines from both sites were further evaluated for agronomic characteristics, disease resistance, and yield. Results showed considerable variation for duration to flowering (40–55 days at three different sites), plant vigor, racemes per plant, reaction to diseases, and grain yield. The crop was extremely vigorous in Naivasha due to supplementary irrigation and fertilization regimes. The results indicated that new high-yielding grain runner bean varieties with resistance to major diseases and tropical adaptation can contribute to improved productivity, food and nutritional security, and resilient livelihoods in the region, and regular supply of raw materials for the canning industry.

KEYWORDS
flowering, long-day, preferred traits, racemes, short-day, varieties

1 | INTRODUCTION

Although runner bean (*Phaseolus coccineus* L.) is traditionally grown in the highlands of eastern Africa, it has received little research attention in the region. Runner bean is also cultivated as either a grain crop or vegetable in Central and South America, the United Kingdom, southern Europe, and Asia, especially in China and Sri Lanka (Suttie, 1969; Caiger, 1995; Kay, 1979; Brink, 2006). The immature, succulent pods are a nutritious vegetable. In the United

Kingdom, runner beans are produced mainly for the vegetable market and are also a popular vegetable in kitchen gardens (Kay, 1979). In eastern Africa, Latin America, and other parts of the world, runner bean is grown mainly for the production of mature seeds, which are eaten as a fresh vegetable, or dried and eaten as a pulse. Kenya and Zimbabwe are the leading producers of vegetable runner bean in Africa (Caiger, 1995). Vegetable runner bean is grown for export to Europe.

In Kenya, grain runner bean is grown at high altitudes (>1,500 m), which limits the area under production. Production of grain-type runner beans is based on unimproved landrace varieties such as Kinangop 2, Nyeri, Dwarf 2, and Dwarf 3. Kinangop 2 and Nyeri are tall climbing type varieties that have traditionally been grown by smallholder farmers in Nyandarua and Nakuru Counties mainly for household consumption and sale in urban and rural markets (Brink, 2006; Kahuro, 1990). Dwarf 2 and Dwarf 3 are short, indeterminate varieties collected from a farmer's field in Ol Joro Orok, Nyandarua County. The dwarf varieties are not widely grown and are apparently recent introductions from unknown sources. These local landraces are short-day types. In contrast, European varieties are long-day plants (Caiger, 1995). The yield of dry mature seeds in Kenya has been estimated at 900 to 1,120 kg/ha (Kay, 1979). According to Suttie (1969), Nyandarua and Nakuru districts are estimated to produce 500–800 tons (t) of dry beans per annum. However, the local varieties are low yielding and susceptible to diseases, especially angular leaf spot, anthracnose, common bacterial blight (CBB), bean common mosaic virus (BCMV), and powdery mildew (Kimani, Mulanya, & Narla, 2014). Although local varieties are adapted to short-day conditions, their pods are tough, nonsucculent, and stringy and, therefore, not suitable for use as vegetables (Kimani et al., 2008). Recently, local canning industries have started canning grain runner bean (Kimani et al., 2008). Compared to its sister species, the common bean (*Phaseolus vulgaris* L.), runner bean has received very little research attention. Runner bean has been used on many occasions for improving the common bean but in very few cases has its own improvement been addressed, although specialists agree on the hardiness of the species against several fungi, bacteria, and viruses, and tolerance to aluminum toxicity. As a result, there are very few runner bean improvement programs in the world and in Eastern Africa (Kimani et al., 2008). In 2005, a regional program was initiated at the University of Nairobi to develop tropically adapted grain runner bean with better yield potential and resistance to diseases (Kimani et al., 2008; Kimani et al., 2016). Populations were developed from crosses between local landraces and long-day European varieties. The populations were advanced as population bulks to F_5, followed by line development up to $F_{6.8}$. The objective of this study was to determine the agronomic potential of advanced bean lines that were previously selected for short-day adaptation, disease resistance, and yield potential in earlier generations, and it was conducted from 2012 to 2014.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

Field experiments were conducted at Kabete Field Station, KALRO-Ol Joro Orok, and at a commercial farm in Naivasha. Table 1 shows some characteristics of these sites. Kabete Field Station lies at an altitude of 1,860 m above sea level and on latitude 1°15′S and longitude 36°44′E (Jaetzold et al., 2006). It falls under upper midland 2 agroecological zone. The area has a bimodal rainfall pattern with peaks in April and November. The annual rainfall is 1,000 mm which is received during the long rains (March–May) and short rains (October–December). The site has maximum and minimum mean temperatures of 24.3°C and 13.7°C, respectively. The soils are very deep, well-drained, dark reddish, friable nitisols which are resistant to erosion.

KALRO-Ol Joro Orok research station is located in Nyandarua County with altitudes around 2,400 m above sea level. The area is classified as an upper highland wheat pyrethrum zone (Jaetzold, Schmidt, Hornetz, & Shisanya,

TABLE 1 Coordinates, altitude, rainfall, temperature, and soil types of the trial sites

Characteristic	Kabete	Ol Joro Orok	Naivasha
Latitude	1°15′S	0°50′S	0°50′S
Longitude	36°44′E	35°13′E	36°22′E
Altitude (masl)	1,860	2,400	1,940
Annual rainfall (mm)	1,000	980	685
Annual maximum temperature (°C)	24.3°	23	24.4
Annual minimum temperature (°C)	13.7°	14	8.2
Soil type	Nitisols	Ando-luvic and verto-luvic Phaeozems	Andosols
Soil pH	6	6.1	6.01
Irrigation	Rainfed	Rainfed	Irrigated

2006). Two major soils found in the area are moderately well-drained, dark reddish-brown ando-luvic and verto-luvic phaeozems, ranging from 0.8 to 1.8 m depth and extremely deep (>1.80 m), well-drained, red to reddish-brown nitisols (Kenya Soil Survey, 1982). The mean annual rainfall is 980 mm, with rainfall occurring throughout the year and peaks in April and July to August. The mean temperature ranges from as low as 14–23°C throughout the year (Jaetzold et al., 2006).

Naivasha Vegpro farm is located south of Lake Naivasha (0°50′S, 36°22′E) at an altitude of 1,940 m above sea level. The average annual rainfall is 685 mm with a bimodal distribution. The first rainy season (long rains) occurs between April and the beginning of July and the second rainy season (the short rains) from the end of August to the beginning of December. However, rainfall is unreliable, and water from the lake is used for irrigation purposes by fresh produce-exporting companies. Naivasha is partially located within the Upper Midland (UM5) with very short cropping seasons and a very uncertain second rainy season and partially in the Lower Highland Ranching Zone (LH5; Jaetzold et al., 2006). The soil type is classified as andosols (Jaetzold et al., 2006). Day length at the three sites is 12 hr (short-day). Temperate varieties such as White Emergo require an additional 3 hr of light to stimulate flowering and pod formation in Kenya.

2.2 | Plant materials and experimental design

Fifty advanced grain runner bean $F_{6.7}$ generation lines selected at Kabete Field Station and Ol Joro Orok during 2012 and 2013 seasons were used in this study. These lines originated from 1,154 single plant selections which were selected from F_5 bulk populations grown at Ol Joro Orok, Subukia and Kabete Field Station between 2009 and 2011. The best 20 lines were subsequently evaluated in Naivasha under irrigation during the 2014 short rains season. Four farmers' varieties (Nyeri, Kin 2, Dwarf 2, and Dwarf 3) were included for comparison with the new lines.

The field experiments were laid out in a randomized complete block design with treatments randomly arranged in each block. Each trial had three replicates. Plants were spaced at 30 cm within rows and 75 cm between rows at Ol Joro Orok and Kabete Field Station. A plot consisted of two rows each with ten plants leading to a total population of 20 plants per 4.5 m^2. The row length was three meters. Trial sites were plowed and harrowed so as to achieve a moderate tilth in the seedbed. Di-ammonium phosphate (18-46-0) fertilizer was applied at a rate of 200 kg/ha and thoroughly mixed with soil. At flowering, the plants were top dressed with calcium ammonium nitrate at a rate of 100 kg/ha. The fields were kept relatively clean of weeds throughout the growing season. In the high input conditions at Naivasha, a standard spacing of 30 cm between plants and 1 m between rows, as used by commercial companies for runner beans, was followed. A plot consisted of two rows, each with 10 plants giving a plant population of 20 plants per 6 m^2. Supplementary irrigation was provided using overhead sprinklers throughout the season. The crop was top dressed with magnesium sulfate, urea, potassium sulfate, N.P.K 17:17:17, and calcium sulfate provided at a rate of 200 kg/ha.

2.3 | Data collection

Data on duration to flowering, plant vigor, number of racemes per plant, disease resistance, pods per plant, and grain yield were recorded using the standard system for the evaluation of bean germplasm described by van Schoonhoven and Pastor-Corrales (1987). Disease and vigor scoring was carried out from flowering to pod filling stages using a nine-point severity scale (1–9), where a score of 1–3 was considered resistant/vigorous, 4–6 intermediate resistance/vigor, and 7–9 as susceptible/poor vigor. Days to flowering were recorded as the number of days from planting to when approximately 50% of the plants in a plot had at least one opened flower. Grain yield was determined by harvesting and threshing pods from all the plants in a plot and recording the weight of the dry grains. Plot yields were used to calculate grain yield in kg/ha.

2.4 | Data analysis

Data from each site were subjected to analysis of variance with Genstat software (v. 15, VSN, UK, 2010) with replicates and genotypes as factors and the measurements as variables. Fisher's protected least significant difference was used for mean separation (Steel, Torrie, & Dickey, 1999). Correlation coefficients among different traits were calculated using procedures described by Steel et al. (1999).

3 | RESULTS

3.1 | Flowering

There were significant ($p < 0.05$) differences for duration to 50% flowering, vigor, disease severity, and number of racemes among the new grain-type runner bean lines (Tables 2–6). At Ol Joro Orok, duration to flowering ranged from 49 to 54 days. In Kabete, duration to flowering varied from 50 to 53 days. The test lines flowered two days earlier at Kabete compared with Ol Joro Orok (Table 2). Although most of the new lines had comparable duration to flowering as check varieties, some flowered later than the checks in all test sites. Some of the new lines such as KAB-RB13-321-190/1, KAB-RB13-301-174, and SUB-OL-RB13-312-252 had relatively early maturation. The test lines flowered earliest at Naivasha (Table 3). Duration to flowering in Naivasha varied from 42 to 49 days.

TABLE 2 Duration to flowering, vigor, and number of racemes per plant of grain runner bean lines rain grown at Kabete Field Station and KALRO-Ol Joro Orok during the 2014 long rain season

	50% Days to flowering			Plant vigor			Racemes per plant		
Genotype	Ol Joro Orok	Kabete	Mean	Ol Joro Orok	Kabete	Mean	Ol Joro Orok	Kabete	Mean
KAB-OL-RB13-426-228	49.7	51.0	50.3	3.7	5.7	4.7	7.0	21.5	14.2
KAB-RB13-108-125	50.3	52.3	51.3	4.7	4.3	4.5	5.0	16.9	11.0
KAB-RB13-120-123/1	50.3	53.3	52.3	3.7	4.3	4.0	4.0	18.9	11.4
KAB-RB13-120-123/2	52.7	53.7	53.2	4.3	5.0	4.7	5.0	15.4	10.2
KAB-RB13-155-122	49.7	51.0	50.3	4.3	5.0	4.7	8.0	11.7	9.9
KAB-RB13-293-209	50.3	53.3	51.8	3.0	5.7	4.3	9.0	11.9	10.5
KAB-RB13-297-144/1	52.3	52.7	52.5	3.7	4.3	4.0	4.0	16.5	10.2
KAB-RB13-297-144/2	50.7	52.3	51.5	4.3	4.3	4.3	8.0	22.7	15.3
KAB-RB13-301-171/1	49.0	53.3	51.2	4.0	5.0	4.5	10.0	13.1	11.5
KAB-RB13-301-171/2	52.3	51.0	51.7	4.3	5.0	4.7	8.0	14.0	11.0
KAB-RB13-301-174	49.3	50.3	49.8	4.7	5.0	4.8	6.0	15.0	10.5
KAB-RB13-303-151	53.0	55.7	54.3	3.3	5.0	4.2	5.0	13.0	9.0
KAB-RB13-308-217	50.3	51.0	50.7	3.7	4.3	4.0	6.0	26.5	16.3
KAB-RB13-312-160	50.7	53.0	51.8	3.7	4.3	4.0	7.0	24.9	15.9
KAB-RB13-313-127/1	49.0	50.7	49.8	3.3	5.0	4.2	9.0	26.9	18.0
KAB-RB13-313-127/2	50.0	51.7	50.8	4.0	4.3	4.2	10.0	25.2	17.6
KAB-RB13-321-185/1	48.7	52.0	50.3	4.3	5.0	4.7	11.0	18.8	14.9
KAB-RB13-321-185/2	49.7	52.0	50.8	2.7	5.0	3.8	14.0	22.0	18.0
KAB-RB13-321-190/1	49.7	50.0	49.8	4.3	4.3	4.3	13.0	19.8	16.4
KAB-RB13-321-190/2	49.3	51.0	50.2	3.7	5.7	4.7	8.0	22.5	15.3
KAB-RB13-326-207	49.0	50.0	49.5	3.3	4.3	3.8	12.0	33.9	22.9
KAB-RB13-329-163/1	49.7	50.7	50.2	4.0	3.7	3.8	5.0	28.3	16.7
KAB-RB13-329-163/2	50.0	53.3	52.2	3.7	5.7	4.7	6.0	13.1	9.6
KAB-RB13-329-164	49.3	51.3	50.3	4.0	5.0	4.5	7.0	14.1	10.5
KAB-RB13-329-166	50.3	52.3	51.3	3.3	3.0	3.2	6.0	22.1	14.0
KAB-RB13-329-167	51.0	51.3	51.2	4.0	5.0	4.5	6.0	29.3	17.6
KAB-RB13-329-172	52.0	50.7	51.3	4.0	4.3	4.2	7.0	30.4	18.7
KAB-RB13-331-225	50.0	53.0	51.5	4.0	5.0	4.5	7.0	17.6	12.3
KAB-RB13-333-223	51.3	51.3	51.3	4.0	5.0	4.5	7.0	23.3	15.1
KAB-RB13-334-130	49.3	50.7	50.0	3.3	3.7	3.5	7.0	23.4	15.2

(Continues)

TABLE 2 (Continued)

Genotype	50% Days to flowering			Plant vigor			Racemes per plant		
	Ol Joro Orok	Kabete	Mean	Ol Joro Orok	Kabete	Mean	Ol Joro Orok	Kabete	Mean
KAB-RB13-334-137	49.3	52.7	51.0	3.3	4.3	3.8	9.0	28.7	18.8
KAB-RB13-336-132	50.7	53.7	52.2	4.0	4.3	4.2	5.0	23.9	14.5
KAB-RB13-341-134	50.3	52.3	51.3	4.0	4.3	4.2	5.0	15.9	10.4
KAB-RB13-343-188	50.3	52.0	51.2	3.7	5.7	4.7	7.0	17.3	12.2
KAB-RB13-364-212/1	48.7	50.7	49.7	3.7	5.0	4.3	11.0	16.1	13.6
KAB-RB13-364-212/2	49.3	51.0	50.2	2.7	3.7	3.2	10.0	29.3	19.6
KAB-RB13-396-210	52.0	53.0	53.0	5.7	4.3	5.0	2.0	20.2	11.1
KAB-RB13-399-219/1	51.0	52.0	51.5	3.7	4.3	4.0	5.0	28.0	16.5
KAB-RB13-399-219/2	49.7	53.3	52.0	3.3	5.0	4.2	5.0	18.2	11.6
KAB-RB13-403-153/1	50.0	52.0	51.0	4.7	5.0	4.8	9.0	26.8	17.9
KAB-RB13-403-153/2	50.3	51.3	50.8	3.7	5.7	4.7	9.0	20.5	14.8
KAB-RB13-46-19	50.0	53.3	51.7	5.3	4.3	4.8	6.0	19.2	12.6
OL-OL-RB13-21-240	54.0	53.3	53.7	3.7	5.0	4.3	1.0	11.1	6.1
SUB-OL-RB13-231-226	52.0	53.0	53.5	4.0	4.3	4.2	7.0	19.3	13.1
SUB-OL-RB13-23-238/1	50.7	51.3	51.0	3.7	5.0	4.3	4.0	14.9	9.5
SUB-OL-RB13-238/2	51.7	51.7	51.7	4.0	5.0	4.5	3.0	14.1	8.6
SUB-OL-RB13-312-252	49.0	49.3	49.2	4.0	4.3	4.2	12.0	33.1	22.5
SUB-OL-RB13-96-237	50.0	51.7	50.8	4.0	5.0	4.5	8.0	13.0	10.5
Mean	50.4	51.9	51.2	3.9	4.7	4.3	7.2	20.5	13.8
Check									
Nyeri	48.7	49.7	49.2	4.7	5.7	5.2	12.0	17.5	14.7
KIN 2	49.3	51.3	50.3	4.0	5.0	4.5	13.0	20.9	16.9
OL-Dwarf 2	49.7	50.3	50.0	5.7	5.7	5.7	10.0	11.1	10.6
OL-Dwarf 3	50.7	49.7	50.2	6.3	5.7	6.0	6.0	6.6	6.3
Mean of checks	49.6	50.3	49.9	5.2	5.5	5.4	10.3	14.0	12.1
Trial Mean	50.3	52.2	51.3	4.0	4.7	4.4	7.0	21.1	14.1
$LSD_{0.05\ Genotype}$	2.2	2.5		1.3	1.9		4.9	16.0	
CV%	1.2	3.0		6.4	15.5		21.7	22.7	

Abbreviations: CV, coefficient of variation; LSD, least significant difference.

TABLE 3 Duration to flowering, vigor, and number of racemes per plant of advanced grain runner bean lines grown under irrigation at Naivasha

Genotype	50% days to flowering	Vigor	Racemes per plant
KAB-RB13-120-123/2	47	1	17
KAB-RB13-294-204/1	47	1	19
KAB-RB13-294-204/2	43	1	18
KAB-RB13-301-171/2	44	1	17
KAB-RB13-309-224/1	47	1	18
KAB-RB13-309-224/2	47	1	21
KAB-RB13-319-182/1	47	1	18
KAB-RB13-319-182/2	44	1	21
KAB-RB13-319-182/3	47	1	13
KAB-RB13-319-182/4	43	1	17
KAB-RB13-329-165	47	1	17
KAB-RB13-333-223/1	46	1	18
KAB-RB13-333-223/2	49	1	18
KAB-RB13-364-212/1	42	1	22
KAB-RB13-364-212/2	43	1	22
KAB-RB13-399-219/2	49	1	16
KAB-RB13-403-149	44	1	23
KAB-RB13-408-220/1	42	1	21
KAB-RB13-408-220/2	45	1	17
KAB-RB13-48-17	45	1	21
Mean	45.4	1	18.7
Checks			
Nyeri	48	1	15
KIN 2	49	1	21
Mean of checks	48.5	1	18
Mean	45.2	0.0	18.7
$LSD_{0.05\ Genotype}$	8.0	0.0	5.1
CV%	8.4	0.0	13.0

Abbreviations: CV, coefficient of variation; LSD, least significant difference.

Plant vigor varied with locations. The test lines were most vigorous under high input conditions at Naivasha and least vigorous under low input conditions at Kabete. Plant vigor ranged from 3 to 6 at Ol Joro Orok and Kabete (Table 2). In contrast, the test lines had a score of one at Naivasha (Table 3).

All test lines flowered under short-day conditions at the three sites indicating effective selection for short-day adaptation. However, formation of flowering racemes varied with locations (Table 2). At Ol Joro Orok, the number of racemes per plant ranged from 3 to 14. At Kabete, the test lines formed 11 to 34 racemes. The number of racemes at Naivasha varied from 13 to 23 (Table 3). The highest number of racemes per plant was recorded in Kabete and the least at Ol Joro Orok (Tables 2 and 3). Most of the lines in all sites had higher number of racemes per plant than the checks.

3.2 | Disease prevalence and severity

Disease incidence and severity varied with locations. Diseases prevalent at the test sites included angular leaf spot, anthracnose, BCMV, CBB, powdery mildew, and rust (Table 4). Angular leaf spot, anthracnose, and BCMV were the most severe diseases at Ol Joro Orok. Powdery mildew was the most prevalent at Kabete (Table 4). Other diseases observed were rust and CBB. Disease incidence was low at Naivasha probably because the trial was conducted under relatively dry off-season conditions and on virgin land without inoculum carry-over. Thirty-nine lines showed resistant reactions to the anthracnose, BCMV, and CBB, while nine lines had intermediate resistance. However, none of the test lines were susceptible to the major diseases. Table 4 shows that the check varieties had higher disease scores compared to the new lines. This suggests

TABLE 4 Reaction of new grain runner bean lines to six major diseases at Kabete and Ol Joro Orok during the 2014 long rain season

	Disease score											
	ALS		Anthracnose		BCMV		CBB		Powdery mildew		Rust	
Genotype	OJ	KAB	OJ	KAB	OJ	KAB	OJ	KAB	OJ	KAB	OJ	KAB
KAB-OL-RB13-426-228	2	1	2	1	2	1	1	1	2	2	1	1
KAB-RB13-108-125	3	1	2	1	2	1	1	1	2	2	1	1
KAB-RB13-120-123/1	2	1	2	1	2	1	1	1	1	2	2	1
KAB-RB13-120-123/2	2	1	2	1	4	1	1	1	1	2	1	1
KAB-RB13-155-122	3	1	3	1	3	1	1	1	1	1	2	1
KAB-RB13-293-209	3	1	2	1	1	1	1	1	2	1	1	1
KAB-RB13-297-144/1	2	1	1	1	1	2	1	1	1	3	1	1
KAB-RB13-297-144/2	2	1	1	1	4	1	1	1	2	3	1	1
KAB-RB13-301-171/1	4	1	2	1	1	1	1	1	1	2	1	1
KAB-RB13-301-171/2	3	1	2	1	2	1	2	1	1	1	2	1
KAB-RB13-301-174	4	2	2	1	2	1	1	2	1	1	2	1
KAB-RB13-303-151	2	1	1	1	1	1	1	1	1	2	1	1
KAB-RB13-308-217	2	1	1	1	3	1	2	1	1	2	1	1
KAB-RB13-312-160	2	1	2	1	2	1	1	2	1	1	2	1
KAB-RB13-313-127/1	2	1	1	1	1	1	2	1	1	2	1	1
KAB-RB13-313-127/2	3	1	2	1	2	1	1	1	1	2	1	1
KAB-RB13-321-185/1	3	1	2	1	2	1	3	1	1	2	1	1
KAB-RB13-321-185/2	3	1	1	1	2	1	1	1	1	2	1	1
KAB-RB13-321-190/1	2	2	1	1	2	1	1	1	1	3	1	1
KAB-RB13-321-190/2	2	1	2	1	3	1	1	1	1	2	1	1
KAB-RB13-326-207	2	2	2	1	1	1	1	1	1	2	1	1
KAB-RB13-329-163/1	2	2	2	1	1	1	1	1	1	2	2	1
KAB-RB13-329-163/2	3	1	2	1	2	1	1	1	1	2	1	1
KAB-RB13-329-164	2	1	1	1	1	2	1	1	1	1	1	1
KAB-RB13-329-166	2	1	2	1	1	1	1	1	1	2	1	1
KAB-RB13-329-167	2	2	1	1	3	1	1	1	1	2	1	1
KAB-RB13-329-172	2	2	3	1	1	2	1	1	1	1	1	1
KAB-RB13-331-225	2	1	2	1	1	1	1	1	1	1	1	1
KAB-RB13-333-223	3	1	2	1	1	1	2	1	1	1	1	1

(Continues)

TABLE 4 (Continued)

Genotype	Disease score: ALS OJ	ALS KAB	Anthracnose OJ	Anthracnose KAB	BCMV OJ	BCMV KAB	CBB OJ	CBB KAB	Powdery mildew OJ	Powdery mildew KAB	Rust OJ	Rust KAB
KAB-RB13-334-130	2	1	2	1	2	2	1	1	1	2	1	1
KAB-RB13-334-137	2	1	1	1	1	1	1	1	1	2	2	1
KAB-RB13-336-132	3	2	1	1	3	2	1	1	1	4	2	1
KAB-RB13-341-134	2	1	1	1	2	1	1	1	2	2	1	1
KAB-RB13-343-188	3	1	2	1	2	1	1	1	1	2	2	1
KAB-RB13-364-212/1	3	1	1	1	1	1	2	1	1	2	2	1
KAB-RB13-364-212/2	2	1	2	1	1	1	1	1	1	1	1	1
KAB-RB13-396-210	3	1	2	1	2	2	1	1	1	1	1	1
KAB-RB13-399-219/1	2	1	1	1	1	1	1	1	2	2	2	1
KAB-RB13-399-219/2	2	1	2	1	2	1	1	1	2	2	2	1
KAB-RB13-403-153/1	3	1	3	1	2	1	1	1	1	2	1	1
KAB-RB13-403-153/2	2	1	2	1	1	1	1	1	1	1	1	1
KAB-RB13-46-19	5	1	4	1	1	1	1	1	1	5	1	1
OL-OL-RB13-21-240	2	1	2	1	1	1	1	1	1	1	1	1
SUB-OL-RB13-231-226	3	1	1	1	2	1	1	1	2	6	2	1
SUB-OL-RB13-238-238/1	2	2	2	1	1	1	1	1	1	1	1	1
SUB-OL-RB13-238-238/2	2	1	2	1	1	1	1	1	1	2	1	1
SUB-OL-RB13-312-252	3	1	2	1	2	2	1	1	1	1	1	1
SUB-OL-RB13-96-237	4	1	3	1	1	1	1	1	1	1	1	1
Mean	2.5	1.2	1.8	1	1.7	1.1	1.1	1.0	1.2	1.9	1.3	1
Checks												
Nyeri	3	4	3	5	4	5	4	3	4	4	3	3
KIN 2	3	3	5	3	4	3	3	3	5	5	4	4
OL-Dwarf 2	3	4	5	4	5	3	4	5	3	4	5	3
OL-Dwarf 3	4	3	4	3	4	3	3	4	5	4	3	3
Mean of checks	3.3	3.5	4.3	3.8	4.3	3.5	3.5	3.8	4.3	4.3	3.8	3.3
Mean	2.6	1.2	1.9	1.0	1.8	1.3	1.3	1.1	1.2	1.9	1.4	1.0
$LSD_{0.05\ Genotype}$	1.5	0.7	1.5	0.3	1.7	0.9	1.1	0.6	0.9	1.3	1.0	0.0
CV (%)	4.1	12.4	10.7	2.5	4.7	9.9	8.8	8.2	10.3	19.9	2.8	0.0

Abbreviations: ALS, angular leaf spot; BCMV, common bacterial blight; CBB, bean common mosaic virus; CV, coefficient of variation; KAB, Kabete; LSD, least significant difference; OJ, Ol Joro Orok.

TABLE 5 Pods per plant and grain yield of advanced grain runner bean lines grown at Kabete and Ol Joro Orok during the 2014 long rain season

Genotype	Pods per plant			Grain yield (kg/ha)		
	OJ	KAB	Mean	OJ	KAB	Mean
KAB-OL-RB13-426-228	55	16	36	7,414	1,958.5	4,686.2
KAB-RB13-108-125	63	19	41	6,351.5	2,776.3	4,563.9
KAB-RB13-120-123/1	51	24	37	6,300.6	2,921.7	4,611.1
KAB-RB13-120-123/2	54	21	38	6,035.2	2,933.7	4,484.4
KAB-RB13-155-122	40	32	36	5,986.4	4,048.4	5,017.4
KAB-RB13-293-209	39	24	31	5,310.6	3,138.2	4,224.4
KAB-RB13-297-144/1	41	26	34	5,299.6	3,726.8	4,513.2
KAB-RB13-297-144/2	34	18	26	5,294.7	2,443.0	3,868.9
KAB-RB13-301-171/1	32	23	27	5,200.1	3,452.0	4,326.0
KAB-RB13-301-171/2	66	19	43	5,198.1	2,380.0	3,789.1
KAB-RB13-301-174	39	14	26	5,101.1	1,922.1	3,511.6
KAB-RB13-303-151	42	14	28	5,098.1	1,938.6	3,518.3
KAB-RB13-308-217	35	19	27	5,090.1	2,565.3	3,827.7
KAB-RB13-312-160	41	27	34	5,042.8	3,771.0	4,406.9
KAB-RB13-313-127/1	38	21	30	4,922.6	2,951.5	3,937.1
KAB-RB13-313-127/2	32	29	31	4,821.7	3,368.2	4,095.0
KAB-RB13-321-185/1	32	23	28	4,792.3	2,374.8	3,583.6
KAB-RB13-321-185/2	52	19	36	4,776	2,639.4	3,707.7
KAB-RB13-321-190/1	39	16	28	4,775.3	2,611.3	3,693.3
KAB-RB13-321-190/2	38	28	33	4,626.6	4,032.3	4,329.5
KAB-RB13-326-207	36	17	27	4,426.7	2,210.9	3,318.8
KAB-RB13-329-163/1	43	27	35	4,422.6	3,398.7	3,910.7
KAB-RB13-329-163/2	26	23	25	4,388.3	2,483.0	3,435.7
KAB-RB13-329-164	36	19	27	4,338.4	2,368.3	3,353.4
KAB-RB13-329-166	32	19	26	4,219.4	2,963.2	3,591.3
KAB-RB13-329-167	36	22	29	4,103.7	3,051.2	3,577.4
KAB-RB13-329-172	35	30	32	4,015	3,695.0	3,855.0
KAB-RB13-331-225	39	23	31	3,848.8	2,401.6	3,125.2
KAB-RB13-333-223	28	30	29	3,643.4	4,104.3	3,873.9
KAB-RB13-334-130	23	24	23	3,484.6	3,235.1	3,359.8
KAB-RB13-334-137	25	23	24	3,461.3	3,357.8	3,409.5
KAB-RB13-336-132	41	25	33	3,439.3	3,540.1	3,489.7
KAB-RB13-341-134	33	27	30	3,338.8	3,390.6	3,364.7
KAB-RB13-343-188	25	16	20	3,312.2	2,039.4	2,675.8
KAB-RB13-364-212/1	31	17	24	3,309.8	2,144.2	2,727.0
KAB-RB13-364-212/2	32	18	25	3,286.5	2,949.6	3,118.0
KAB-RB13-396-210	34	17	25	3,245.7	2,352.4	2,799.1
KAB-RB13-399-219/1	30	16	23	3,188.1	2,269.7	2,728.9
KAB-RB13-399-219/2	37	30	33	3,121.6	3,900.0	3,510.8
KAB-RB13-403-153/1	23	14	18	3,047	1,674.5	2,360.7
KAB-RB13-403-153/2	23	15	19	3,038.9	1,887.6	2,463.3
KAB-RB13-46-19	24	23	23	3,012.8	2,758.3	2,885.5

(Continues)

TABLE 5 (Continued)

Genotype	Pods per plant OJ	KAB	Mean	Grain yield (kg/ha) OJ	KAB	Mean
OL-OL-RB13-21-240	28	29	28	2,988.8	3,758.5	3,373.6
SUB-OL-RB13-231-226	25	26	26	2,858.5	3,033.7	2,946.1
SUB-OL-RB13-238-238/1	28	16	22	2,841.2	1,910.4	2,375.8
SUB-OL-RB13-238-238/2	26	22	24	2,805.4	2,604.9	2,705.1
SUB-OL-RB13-312-252	29	23	26	2,635.6	3,472.9	3,054.3
SUB-OL-RB13-96-237	23	24	23	2,621.7	3,529.1	3,075.4
Mean	35.7	21.8	28.8	4,247.5	2,884.1	3,565.8
Checks						
Nyeri	40	20	30	4,830.2	2,785.7	3,808.0
KIN 2	33	22	28	3,464.3	2,249.4	2,856.8
OL-Dwarf 2	32	13	23	2,875.9	1,895.1	2,385.5
OL-Dwarf 3	22	15	18	1,833.3	1,834.6	1,833.9
Mean of checks	31.8	17.5	24.8	3,250.9	2,191.2	2,721.1
Mean	35	23	29	4,153	3,034.6	3,593.8
$LSD_{0.05\ Genotype}$	22	14		2,904.8	2,276.9	
CV%	5.2	7		2.4	10.1	

Abbreviations: CV, coefficient of variation; KAB, Kabete; LSD, least significant difference; OJ, Ol Joro Orok.

effective selection for resistance to diseases after eight generations of field testing and selection under variable environmental conditions. It also indicates that these lines have better yield stability due to their combined resistance to multiple diseases.

3.3 | Yield and its components

Results showed that there were significant differences ($p < 0.05$) for the number of pods per plant and grain yield among the new grain runner bean lines (Tables 5 and 6). There was considerable variation for the number of pods per plant among the test lines and test sites. Pods per plant varied from 2 to 66 among the test lines. Among the check varieties, pods per plant varied from 13 to 40. The highest number of pods per plant was recorded at Ol Joro Orok (35), while the lowest was recorded at Naivasha (15). Pods per plant ranged from 23 to 66 at Ol Joro Orok and from 14 to 30 at Kabete (Table 4). At Naivasha, pods per plant varied from 2 for KAB-RB13-333-223/1 to 31 for KAB-RB13-294-204/1(Table 6). KAB-RB13-108-125 and KAB-RB13-301-171/2 had the highest number of pods per plant across sites. Eleven lines at Ol Joro Orok, 24 at Kabete, and six lines at Naivasha had more pods per plant than the checks (Tables 5 and 6).

The test lines showed considerable variation for grain yield. Mean grain yield across sites varied from 2,360 to 5,010 kg/ha among the test lines and from 1,833 to 3,808 kg/ha for the check varieties. Grain yield varied also with sites. Grain yield ranged from 2,622 to 7,414 kg/ha at Ol Joro Orok, 1,675 to 4,104 kg/ha at Kabete and from 876 to 14,472 kg/ha at Naivasha, suggesting that grain yield was influenced by genotype, location, adaptation to high altitude, and crop management (Tables 5 and 6). At Naivasha, the new lines had an 80% yield advantage over the checks. However, the yield advantage of new lines was lower at Ol Joro Orok (35%) and Kabete (32%). Average grain yield in Kabete was 3,034.6 kg/ha compared to 4,153 kg/ha at Ol Joro Orok and 7,254 kg/ha at Naivasha. This suggested that test sites indicated the potential of the test lines under low-, medium-, and high-yielding environments. Sixteen lines had better yield than the best yielding check, Nyeri, (3,808 kg/ha). However, apart from one, all the new lines had higher grain yield than the checks at Naivasha. The best yielding lines at Kabete and Ol Joro Orok were KAB-RB13-155-122 (5,117 kg/ha), KAB-OL-RB13-426-228 (4,686 kg/ha), and KAB-RB13-120-123/1(4,611 kg/ha). The best yielding lines at Naivasha were KAB-RB13-294-204/2 (14,472 kg/ha), KAB-RB13-364-212/1 (12,496 kg/ha), and KAB-RB13-364-212/2 (10,923 kg/ha) (Tables 5 and 6).

There was no correlation between 50% duration to flowering and other traits under low input conditions at Kabete and Ol Jorok (Table 7). However, under high input conditions at Naivasha, duration to flowering was negatively correlated with number of racemes per plant ($r = -0.45$*) and grain yield ($r = -0.73$**). This implied that genotypes which took longer to flower under high input conditions,

TABLE 6 Pods per plant and grain yield of advanced grain runner bean lines grown at Naivasha during the 2014 short rain season under irrigation

Genotype	Pods per plant	Grain yield (kg/ha)
KAB-RB13-120-123/2	10	4,239
KAB-RB13-294-204/1	17	7,436
KAB-RB13-294-204/2	31	14,472
KAB-RB13-301-171/2	15	4,743
KAB-RB13-309-224/1	11	5,584
KAB-RB13-309-224/2	16	6,811
KAB-RB13-319-182/1	11	5,826
KAB-RB13-319-182/2	13	7,172
KAB-RB13-319-182/3	7	2,944
KAB-RB13-319-182/4	16	8,153
KAB-RB13-329-165	17	8,866
KAB-RB13-333-223/1	2	876
KAB-RB13-333-223/2	10	4,248
KAB-RB13-364-212/1	30	12,496
KAB-RB13-364-212/2	21	10,923
KAB-RB13-399-219/2	10	4,224
KAB-RB13-403-149	19	9,869
KAB-RB13-408-220/1	21	10,580
KAB-RB13-408-220/2	22	10,120
KAB-RB13-48-17	11	5,496
Mean of test lines	**15.5**	**7,253.9**
Checks		
Nyeri	16	2,732
KIN 2	18	2,944
Mean of checks	**17**	**2,838**
Mean	15.4	7,254.0
*$LSD_{0.05\ Genotype}$	14.0	7,293.6
CV%	13.1	12.8

Abbreviation: CV, coefficient of variation.

*Least significant difference.

formed fewer racemes per plant, which contributed to lower grain yields. The number of racemes per plant correlated positively with pods per plant ($r = 0.28$**) and grain yield ($r = 0.32$**) in low and high input conditions, and but negatively with vigor ($r = -0.42$**). Pods per plant were highly positively correlated with grain yield ($r = 0.90$**) in low and medium input conditions and also in high input conditions ($r = 0.87$**). However, pods per plant were negatively correlated with vigor ($r = -0.24$*). Plant vigor was negatively correlated with grain yield ($r = -0.27$**) (Table 7). This suggested that vigorous vegetative growth in some genotypes may have contributed to lower pod set and eventually to lower grain yield.

4 | DISCUSSION

The objective of the runner bean breeding program at the University of Nairobi is to develop improved tropically adapted short-day varieties with better agronomic potential to meet both producer and consumer requirements. At present, smallholder farmers cultivate traditional grain-type landraces for domestic consumption and for sale in local markets and for processing factories. Vegetable exporting companies produce long-day varieties which require additional artificial lighting to stimulate flowering and pod formation. This increases production costs and reduces the competitiveness in export destinations. There is no seed system for grain-type runner beans and farmers use farm-saved seeds. Vegetable exporting companies have to import seed of the varieties they produce. This further increases production costs. The lines developed by our program may provide better options to both smallholder farmers and large-scale vegetable exporters. This study showed that the new grain-type runner bean lines flowered without extended light at Kabete, Naivasha, and Ol Jorok Orok. The duration to flowering ranged from 49 to 54 days at Ol Joro Orok and 50–53 days at Kabete. This concurred with Kimani et al. (2014) who found that runner bean flowered in 49–53 days at Kabete, 46–54 days in Ol Joro Orok, and from 42–49 days at Naivasha. Mulanya and Kimani (2014) also found that the duration to flowering in runner bean lines ranging from 50 to 52 days in both Kabete and Ol Joro Orok. The significant differences for days to flowering in advanced lines in Kabete and Ol Joro Orok can be attributed to genetic differences among genotypes and environmental factors at the test sites. In Naivasha, where higher temperatures were recorded (mean of 20°C), genotypes flowered earlier. However, duration to flowering was longer at Kabete (17.7°C) and Ol Joro Orok (14.6°C) due to low temperatures, which coincided with coldest months of the year. Wallace, Paula, and Zobel (1991) also found that the number of days to flowering of common beans is influenced by the temperature which alters the rate of vegetative development and causes faster flower development under higher temperatures. George (1988) also reported that at higher elevations with lower temperatures, duration to flowering was longer in common bean and soybean.

The significant differences in plant vigor across sites could be attributed to genotypic responses to changes in environmental conditions and management practices. The test lines were most vigorous under high input conditions at Naivasha and least vigorous at Kabete. However, there were no significant differences among advanced lines grown in Naivasha. The crops were highly vigorous probably due to higher fertilizer application rates and irrigation which favored the growth of runner beans. The low plant vigor at Kabete and Ol Joro

TABLE 7 Correlation matrix among agronomic traits of grain runner bean lines grown under low and medium input conditions at Kabete and Ol Joro Orok, and under high input conditions at Naivasha

	50% duration to flowering	Number of racemes per plant	Pods per plant	Vigor	Grain yield (kg/ha)
50% duration to flowering	1				
Number of racemes per plant	−0.17 (−0.45*)†	1			
Pods per plant	0.04 (−0.58*)	0.28** (0.41)	1		
Vigor	0.13	−0.42**	−0.24*	1	
Grain yield kg/ha	0.03 (−0.73**)	0.32** (0.46*)	0.90** (0.87**)	−0.27**	1

*, **Correlation coefficient significant at 0.05 and 0.01 probability levels, respectively;
†Correlation coefficients in brackets are for high input conditions at Naivasha.

Orok was attributed to low fertility and moisture stress during the growing season. Crops at Kabete and Ol Joro Orok were wholly rainfed.

Differences in the number of racemes per plant across sites were probably due to genotypic effects and other factors that influence pod set and retention. These lines originated from crosses between long-day plants which fail to flower or flower poorly under short-day tropical conditions, and short-day parents. However, the segregating populations showed considerable variation in flowering and pod set (Kimani et al., 2014; Mulanya and Kimani et al.,2014). Although selection reduced the amount of variation for these traits, it is plausible that segregation continued to later stages, especially considering the out-crossing behavior of runner bean. This could have contributed to the observed variation in the number of racemes formed. The high number of racemes per plant in Kabete can be explained by relatively cooler weather at flowering which favored pod retention. The low number of racemes per plant in Naivasha was as a result of flower abortion probably due to heat stress. Day temperatures in Naivasha were as high as 33°C. The results concurred with Mulanya and Kimani (2014) who found that the number of racemes per plant of runner bean lines grown in Kabete was low due to water stress that was experienced during the trial period. Moisture stress at the start of the season at Ol Joro Orok could also have contributed to the low number of racemes per plant. Hadjichristodoulou (1990) reported that runner beans are adapted to cooler climates and their growth in areas with high temperatures yields low seeds due to poor flowering. However, they give satisfactory yields when planted at cooler areas with low temperatures.

The new runner bean lines used in this study did not show susceptibility to any of the prevalent diseases at the test sites. They showed higher levels of resistance compared with checks. Runner beans are known to have resistance to most bean diseases and have been used to improve disease resistance in common bean (Brink, 2006). Results of this study confirmed previous reports that earlier generations of these lines were resistant to BCMV, CBB, and rust (Kimani et al., 2014). Thirty-nine lines had multiple resistance to prevalent diseases. Resistance to disease will contribute to reduced production costs and improved yields.

Pods per plant differed significantly among advanced lines in both Naivasha and Ol Joro Orok. Pods per plant are influenced by the number of racemes per plant. However, the higher number of racemes per plant in Kabete was not reflected in pods per plant. This could be due to the abortion of flowers and young pods, probably because of water stress. In Naivasha, there were a low number of racemes and pods per plant despite high levels of nutrients and enough soil moisture. This was probably due to high vegetative growth hindering access to adequate sunlight. This was evidenced by the high number of racemes observed on the upper side of the runner bean canopy facing the sunlight. Failure of the crop to obtain enough sunlight led to flower abortion and few pods. In Emam, Shekoofa, Salehi, and Jalali (2010) and Gebeyehu (2006), low yield is associated with adverse effects of yield components such as the number of pods per plant, the number of seeds per pod, and seed mass. High grain yield despite low pods per plant in Naivasha could be due to the high number of seeds per plant and seed mass owing to the availability of adequate soil moisture during the cropping season.

The new lines showed considerable variation for grain yield. The grain yield varied from 876 to 14,472 kg/ha across the sites. Grain runner bean is predominantly grown by smallholders in Meru, Nakuru, and Nyandarua Counties. In Kenya, the yield of dry mature seeds from smallholders has been estimated to be about 900 to 1,120 kg/ha (Kay, 1979). Nakuru and Nyandarua Counties are estimated to produce between 500 and 800 t which are marketed annually (Suttie, 1969). The yield levels of the new lines therefore represent a significant improvement of runner bean productivity through breeding. The higher yield in Ol Joro Orok compared to Kabete could be due to cooler and wetter conditions. Mulanya and Kimani (2014) reported that runner bean lines grown at Ol Joro Orok had higher racemes per plant and pod yield due to a cooler climate and adequate rainfall. The number of racemes per plant correlated positively with pods per plant and grain yield indicating that the higher the number of racemes, the higher the number of pods and grain yield. Results showed that productivity of runner bean can be increased by improved not only by genetically superior varieties but also by use of higher input levels. Thus, grain yield of test lines increased by 103 percent under high input conditions. In contrast, yield of check varieties increased by only 4.3 percent, suggesting that the new lines were more responsive to external inputs. The higher grain yield of test lines under high input conditions was attributed to improved plant vigor and formation of more racemes per plant. However, for growers to benefit from utilization of improved runner bean lines, it will be necessary to initiate a certified seed production, distribution, and awareness creation program. This may take two to three years because of regulatory requirements and resource mobilization. However, an informal seed delivery system may take a shorter period because runner bean is not under compulsory certification. There is no certified seed production program for runner bean in Kenya and the region in general at present.

5 | CONCLUSION

Minimal research has been done on runner bean. This study was the first in eastern and central Africa to develop new grain-type runner lines and determine their agronomic potential. The new lines showed high yield potential, resistance to diseases, and adaptation to short-day conditions. They flowered at the three sites without extended light. Grain yield ranged from 1,888 to 7,414 kg/ha at Kabete and Ol Joro Orok under rainfed conditions and from 876 to 14,472 kg/ha under irrigation at Naivasha. Compared with the checks, the new lines had a yield advantage of 80% at Naivasha, 35% at Ol Joro Orok, and 32% at Kabete. Several lines with better yields than the local varieties were identified. They included KAB-RB13-294-204/2, KAB-RB13-364-212/1, KAB-RB13-364-212/2 (Naivasha), KAB-OL-RB13-426-228, KAB-RB13-108-125, KAB-RB13-120-123/1, KAB-RB13-120-123/2, and KAB-RB13-155-122. The new lines had better pod set at Ol Joro Orok than Kabete. Considering the increasing demand for grain runner bean, especially by the canning industry, and consumer preferences for a wide range of runner bean types, the results of this study suggest that the new lines can contribute to increased production due to their multiple resistance to diseases and high yield potential. They can also contribute to the improved availability of raw materials to canning companies. The new high-yielding grain runner bean varieties with resistance to major diseases and tropical adaptation can contribute to improved productivity, food and nutritional security, and resilient livelihoods in the region.

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