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GAIN AND PERFORMANCE IN YIELD AND MICRONUTRIENT CONCENTRATION IN COMMON BEAN IMPROVEMENT

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ABSTRACT

Common bean (*Phaseolus vulgaris* L.) is a staple and nutritious leguminous food crop for all income categories in Africa. Efforts to improve its yield performance and nutritional components, especially iron and zinc have resulted in release of several varieties in the sub-Sahara African region. The objective of this study was to assess genetic progress in varieties released in 12 African countries through the Pan African Bean Research Alliance (PABRA) from 1973 to 2017, to inform current breeding decisions. A total of 214 released varieties, land races and breeding lines, of bush and climbing beans were evaluated for yield, micronutrient (Fe and Zn) concentration, and phenology in three locations (Kawanda and Kachwekano in Uganda, and Kitengule in Tanzania) in 2017/2018. There were significant differences ($P<0.01$) among genotypes for all traits, except days to maturity (DPM). Genotype x environment interaction was also significant ($P<0.05$) for all assessed traits, except for iron in climbing beans. Across environments, repeatability (H^2) was greater than 0.50 for all traits, except for DPM in climbing beans. Annual rates of genetic yield gains were 4.41 and 4.57 kg ha^{-1} for large and small seed bush beans, and -2.74 and 21.6 kg ha^{-1} for large and small seeded climbers. Similarly, gains in seed iron (FESEED) were 0.40 and 0.17 ppm for bush and climbing beans, respectively. These represented an annual relative gain over the oldest varieties of 0.6 and 0.7% kg ha^{-1} for yield of large and small seeded bush beans, -0.3 and 1.6% kg ha^{-1} for yield of large and small seeded climbers, 0.6 and 0.2% ppm for FESEED of bush and climbers. Overall, genetic progress was slow for both yield and FESEED.

Key Words: Biofortification, genetic gain, *Phaseolus vulgaris*, zinc

RÉSUMÉ

Le haricot commun (*Phaseolus vulgaris* L.) est une légumineuse vivrière de base et nutritive pour toutes les catégories de revenus en Afrique. Les efforts visant à améliorer ses performances de rendement et ses composants nutritionnels, en particulier le fer et le zinc, ont abouti à la diffusion de plusieurs variétés dans la région de l'Afrique subsaharienne. L'objectif de cette étude était d'évaluer les progrès génétiques des variétés diffusées dans 12 pays africains par le biais de l'Alliance panafricaine de recherche sur le haricot (PABRA) de 1973 à 2017, afin d'éclairer les décisions de sélection actuelles. Un total de 214 variétés publiées, races terrestres et lignées de haricots nains et grimpants ont été évaluées pour le rendement, la concentration en micronutriments (Fe et Zn) et la phénologie dans trois endroits (Kawanda et Kachwekano en Ouganda et Kitengule en Tanzanie) en 2017 /2018. Il y avait des différences significatives (P<0,01) entre les génotypes pour tous les caractères, sauf le nombre de jours jusqu'à la maturité (DPM). L'interaction génotype x environnement était également significative (P < 0,05) pour tous les caractères évalués, à l'exception du fer dans les haricots grimpants. Dans tous les environnements, la répétabilité (H^2) était supérieure à 0,50 pour tous les caractères, à l'exception du DPM chez les haricots grimpants. Les taux annuels de gains de rendement génétique étaient de 4,41 et 4,57 kg ha^{-1} pour les haricots nains à grosses et petites graines, et de -2,74 et 21,6 kg ha^{1} pour les haricots grimpants à grosses et petites graines. De même, les gains en fer des graines (FESEED) étaient de 0,40 et 0,17 ppm pour le haricot nain et le haricot grimpant, respectivement. Celles-ci représentaient un gain relatif annuel par rapport aux variétés les plus anciennes de 0,6 et 0,7% kg ha^{-1} pour le rendement des haricots nains à grosses et petites graines, -0,3 et 1,6% kg ha^{-1} pour le rendement des haricots grimpants à grosses et petites graines, 0,6 et 0,2 % ppm pour les gains en fer des graines (FESEED) de haricots nains et de haricot grimpant. Dans l'ensemble, le progrès génétique a été lent tant pour le rendement que pour les gains en fer des graines (FESEED).

Mots Clés : Biofortification, gain génétique, *Phaseolus vulgaris*, zinc

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is a widely consumed legume in Africa, owing to its affordability, palatability and nutritional value. More than 400 million people in sub-Saharan Africa regularly consume beans in their varied diets (CIAT, 2018). To sustain its productivity and marketability amidst the many biotic and abiotic stresses, continuous improvement for higher yields, disease resistance, nutrition value (especially micronutrients), processing quality and consumer traits has been ongoing.

Obtaining genetic gain in traits of interest, primarily requires genetic diversity in the breeding populations, besides appropriate breeding and phenotyping methods, and demand-led breeding, among others (Ojiewo *et al.*, 2017). Crossing elite genotypes is a key strategy for improving quantitative traits such as yield in a short time, but new sources of alleles need to be regularly introduced into the breeding programme for long term diversity maintenance (Falk, 2010). In the case of inadequate genetic variation for a specific trait among the elite germplasm, wide crosses to exotic germplasm or wild species is inevitable (Sullivan, 1988). To improve common bean (*Phaseolus vulgaris*) genetic diversity for pest and disease resistance, drought and heat tolerance, and tolerance to aluminium toxicity, low soil phosphorus and seed iron, the bean programme at the Alliance of Bioversity and International Centre for Tropical Agriculture (CIAT) has utilised other Phaseolus species (Beebe *et al.*, 2011).

Advances in marker assisted selection have enhanced gains attained in bean traits improvement; although vast opportunities to increase genetic gain and efficiency using genomic tools, improved phenotyping methods and demand-led breeding approaches, need more exploitation (Ojiewo *et al.*, 2017; Assefa *et al.*, 2019). Recently, breeding programmes have adopted product profiling, a demand-led breeding approach, which is expected to enhance genetic gain realisation, and hence the delivery of farmer acceptable varieties.

A product profile refers to a full range of technical attributes of a new variety to be successfully released onto a market segment (Ragot *et al.*, 2018). A new variety with superiority over the older variety being replaced is, therefore, easy to visualise, develop and select. In common bean, products have been described in terms of the grain type (size and colour attributes), growth habits (bush and climbers), or use (dry bean, canning bean or green bean) (Buruchara *et al*., 2011), among others. Based on these attributes, in addition to disease resistance or seed iron, seven product profiles, including large white, large red, large red mottled, small red, small white, sugar (speckled) bean, and yellow beans, were developed across three East African countries (Mukankusi *et al*., 2019).

Through the efforts of the Alliance of Bioversity International and CIAT (ABC) and other members of the Pan African Bean Research Alliance (PABRA), many improved beans have been developed and disseminated in Africa. In 1950, the first improved bean variety (PAN148) was released in Zimbabwe and since then, over 33 African countries have released their preferred varieties (PABRA database, http://database.pabra-africa.org). Buruchara *et al.* (2011) reported the release of over 200 new varieties in Africa from 2003 to 2011. As such, increases of 10 to 40% in on-farm yields of new varieties above older ones have been realised in most African countries where bean breeding has been on going (Mukankusi *et al*., 2019). For example, on farm yields have increase from less than 1000 kg ha^{-1} in 2001 to 1773.4 kg ha^{-1} in Ethiopia, 1500 kg ha^{-1} in Uganda, 1479.5 kg ha^{-1} in Ghana, and 1366.1 kg ha^{-1} in Cameroon in 2020 (FAO, 2001-2020).

Among the released varieties are superior yielding bio-fortified beans with multiple stress resistance under African conditions (Ojiewo *et al*., 2017). Iron biofortification was initiated in PABRA by collection and phenotyping for seed iron and zinc in African germplasm in 1996 (Amongi *et al*., 2018). Since then, studies targeting hybridization of high iron beans (HIB) by HIB, and also HIB targeting specific adaptations were designed by the ABC in Palmira and Uganda, and other members of PABRA such as Kenya and Rwanda (Mulambu *et al*., 2017; Kimani and Warsame, 2019; Amongi *et al*., 2021). Mean seed iron and zinc concentrations were 65 and 30 ppm for bush beans, and 71 and 31 ppm for climbers, in the first regional nutrition nursery in PABRA (Amongi *et al*., 2018). It has since increased to 75 and 39 ppm for bush and 73 and 41 ppm for climbers in some recently improved varieties (Amongi *et al*., 2021). Previous values for genetic gain in seed iron in common bean was unavailable in literature. The objective of this study was to assess genetic progress in varieties released in Africa, through the Pan African Bean Research Alliance (PABRA) from 1973 to 2017 to inform current breeding decisions.

MATERIALS AND METHODS

Genotypes description. A total of 214 released varieties, land races and breeding lines were used in this study. Out of 214 genotypes, 115 which were released in 12 African countries, were considered for estimating relative genetic gain (Table 1). The 115 varieties consisted of 56 large and 32 small seeded bush beans (type 1 and 2), and 16 large and 11 small seeded climbers (type 3 and 4), that were released from 1973 to 2017 (Table 2).

Study sites. The study was conducted in three locations; namely the National Agricultural Research Laboratories (NARL) Kawanda, Kachwekano Zonal Agricultural Research and Development Institute (KAZARDI), and Kitengule Prison Farm. The NARL-Kawanda and KAZARDI are in the central and southwestern Uganda at 0°252 N, 32° 31’E and at an elevation of 1190 m above sea level (masl), and 1° 15’S, 29° 57’E at an elevation of 2200 masl, respectively. Kitengule is in Kagera region, Tanzania, located at 1° 26' 15’S, 31° 10' 25’E, at an elevation of 1276 masl.

Trial establishment. Planting at the three sites was done during second and first rainy seasons of 2017 and 2018: September to December and April to July, respectively. The genotypes

TABLE 1. Attributes of common bean germplasm released in twelve African countries from 1973 to 2017, and check genotypes

Varieties	BU	KE	DRC	ET	RW	UG	TZ	SW	MA	ZI	ZA	MO	Source	Pedigree	GH	PSC	SSC	SCP
FLORA DE MAYO	1987	1996			1991		2006						CIAT	G5701/ G3872	C	Pink	Cream	Mottled
HM21-7 (SEPE)	1987		2010										CIAT		B	Red	Cream	Mottled
G685 (VUNIKINGI)	1995	1996	2004		1991	1999							CIAT	MONCURE NO.12	C	Pink	Red	Striped
AND10 (BISHAZA)	1998		1991										CIAT	G5702/ G12488	C	Cream	Pink	Striped
MOORE 88002 (AKARYOSHE or NAROBEAN3)	1999					2016							NARS		B	Yellow		None
CAL96 (K132)	1999		2008	2012		1994							CIAT	CALIMA2/ ARGENTNO1	B	Red	Cream	Mottled
TWUNGURUMIRWANGO	2006															Red		None
KATB1 (MBUNDUGURU or SELIAN 13 or ADA)	2008	1998		2015			2017						NARS		B	Yellow		None
KATB9 (DANDESU or INAKAYOBA or SELIAN 12)	2008			2014			2017						NARS		B	Red		None
KATX56	2008	1999											NARS		B	Red		None
KAX69	2008	1998											NARS		B	Red	Cream	Mottled
MUKUNGUNGU	2008												Other CGIAR		SB	Others		None
BIHOGO (MLV-206/96B)	2008															Yellow	Red	Striped
Bisera (LM9220492)	2008															Red	Cream	Mottled
MUSENGO (MLB12298B)	2008															Cream	Others	
VCB81013 (NYAWERA)	2009		2006										CIAT	GUANAJUATO22/ CUARENTINOH6 =ZRE6	C	White		None
AMAHUNJA	2009															Yellow		None
GASIRIDA	2010				2010								NARS		C	Purple		None
GLP2 (K20)	2010	1982	2010	2011									Other CGIAR		B	Red	Cream	Mottled
M'SOLE (MUSORE or UBUSOSERA)	2011		2006												SB	Others		None
KILYUGARAMYE (RWR2091)	2011															Red		None
MAC44 (MAGORORI or SELIAN 14 or NAROBEAN4C)	2015				2010	2016	2017						CIAT	AND930/ G12722	C	Red	Cream	Mottled
RWV1129 (MURENGETI or URUVUZO or SELIAN 15)	2015				2010		2017						CIAT		C	Pink	Cream	Speckled
RWR1092 (GAHAMA)	2017												NARS		B	Red		None
Mwetamania		1982														Cream	Others	
KK8 (FLORA)		1997											CIAT		SC	Red	Cream	Mottled
RWR719 (OMO95)		1998		2003	1991										B	Red		None
MLB49-89A		2006	1991		1997								CIAT		SB	Black		None
G2333 (LYAMUNGU 85)		2007	1990		1991	1999							CIAT		C	Red		None
SCAM-80CM/15 (UMUBANO)		2007											CIAT		SB	Red	Cream	Mottled
AFR708		2008	2006										CIAT	BEAN98/ ZAA39// ZAA39	B	Red	Cream	Mottled
GLP-585 (RED HARICOT)		2008											CIAT		SB	Red		None
KK20 (CIANKU)		2008											CIAT		C	Red		None
KAT-SW-12 (KENYA MALI)		2015													SB	White		None
KAT SW-9 (SELIAN9 or SWP09)		2015														White		None
DAB299 (Nyota)		2017														Red	Cream	Mottled
G2858			1986													Cream	Others	
ROBA 1 (CROPS-SEMANHYIA or ROBA)			1990				2010						Landrace		B	Cream		None
RWR362 (M'MAFUTALA)			1991													Red		None

TABLE 1. Contd.

Varieties	BU	KE	DRC	ET	RW	UG	TZ	SW	MA	ZI	ZA	MO	Source	Pedigree	GH	PSC	SSC	SCP
AND620			1995													Red		None
NGWAKUNGWAKU			2000										NARS		B	Yellow		None
XAN76			2002										CIAT		B	Cream		None
CNF5520			2003												SB	Brown		None
DC12496-50 (MBIDI)			2003										CIAT		SB	Cream	Others	Mottled
KABULANGETI			2004				1999				2007		CIAT		SB	Purple	Cream	Speckled
A445 (AB136)			2006										CIAT		C	Red		None
ACC714			2006										NARS		SB	Black		None
CODMLB001			2006										NARS		B	Purple	Cream	Mottled
CODMLB033			2006										CIAT		B	Red	Cream	Mottled
NUA35			2006						2017				CIAT		B	Red	Cream	Mottled
RWR2154 (NAROBEAN1)			2006		2010	2016							NARS		SB	Cream	Pink	Striped
RWR2245 (NAROBEAN2)			2006		2010	2016							NARS		B	Red	Cream	Mottled
UBR(92)25 (KABALABALA)			2006						2002	2005			CIAT	MCM3031// EMP81/ BAT388)	SC	White	None	
ZKA93-10M/95			2006										CIAT		SB	Yellow		None
DRK64 (NAIN DE KYONDO)			2007										CIAT	AFR185/ AFR88	SC	White		None
NUA 45			2007					2013	2009	2010	2012		CIAT	CAL96// CAL96/ G14519	B	Red	Cream	Mottled
NYIRAMUHONDO (NAROBEAN5C)				2007			2016							NARS		C	Yellow	None
SELIAN97 (BWANA SHAMBA)			2010				1997							TMO110/ PVA782	B	Red		None
MAHARAGISOYA			2011										CIAT		SB	Cream		None
NUA 99			2011										CIAT		B	Red	Cream	Mottled
ECAPAN021			2013										CIAT		SB	Red		None
MEX 142				1973									CIAT		SB	White		None
AWASHMELKA				1999											SB	White		None
SUG 131 (KHOLOPHETHE or MALEPA or GOLDEN STALITE)					1999		1999		2008	2002	2007		CIAT	VAX7/ AND77	B	Cream	Pink	Striped
AFR703				2007									CIAT		B	Red	Cream	Mottled
VAX2 (GABISA)				2007											SB	Cream		None
MONTCALM				2007														
URUGEZI (1378/4)					1991											Red	Cream	Mottled
CAB19					2002								CIAT		C	White		None
CAB2					2010								CIAT	G20557/ VCB81020	C	White		None
MAC42					2010								CIAT	AND930/ G12722	C	Cream	Pink	Striped
RWR1180 (MUTIKI)					2010								NARS		B	Pink		None
SER16					2010								CIAT	(RAB651/TIO CANELA 75)F1/ (RAB608/ SEA15)F1/ MC2PMQMC27CMCMC	B	Red		None
RWV2887 (GIRUBUZIMA)					2012								NARS	CAB2/ LAS400	C	Cream	Pink	Striped
RWV3006 (NSHUTINZIZA)					2012								NARS	CAB2/ BUBERUKA	C	White		None
RWV3316 (VUZIMPUNDU)					2012								NARS	CAB2/ LAS400	C	Red		None
KANYEBWA													Landrace		B	Pink	Red	Striped
OCUC													Landrace		B	Black		None
MASSINDI YELLOW LARGE														Landrace	SB	Yellow		None
MASSINDI YELLOW SMALL														Landrace	B	Yellow		None
K131 (MCM 5001)						1994								IVTB31607/ RAB71	B	Cream	Others	Mottled
NABE1						1995									B	Red	Cream	Mottled
NABE2 (MCM 1015)						1995								IVT831629/ BAT1554	B	Black		None
NABE3 (MCM 2001)						1995								IVT831607/ RAB71	SB	Red		None
NABE10 (UMUBANO or BUCHUPULI)							1999							CIAT		C	Red	

TABLE 1. Contd.

Varieties	BU	KE	DRC	ET	RW	UG	TZ	SW	MA	ZI	ZA	MO	Source	Pedigree	GH	PSC	SSC	SCP
None																		
NABE4						1999							CIAT	SUG58/ CAL103	B	Red	Cream	Mottled
NABE5						1999							CIAT	AFR88/ AFR199	B	Red	Cream	Mottled
NABE6						1999							Landrace	Mults UBR(25)MR	SB	White		None
NABE8C (NGWINURARE)						1999								59/1-2	B	Red		None
NABE9C (GISENYI)						1999							CIAT		C	Cream	Others	Mottled
NABE11 (AFR 721)						2003							CIAT		B	Red	Cream	Mottled
NABE12C (MASAVU or MAZONGOTO)							2003						CIAT	GOLDO/ A487	C	Cream	Purple	Striped
NABE13 (RWR 1946 or MUZAHURA)							2006							CIAT	B	Red		None
NABE14 (RWR 2075)						2006									B	Pink		None
NABE15						2010							CIAT	Kanyebwa/ P120762	B	Pink	Red	Striped
NABE16						2010							CIAT	Kanyebwa/ G2333	SB	Red	Cream	Mottled
NABE17						2012								Kanyebwa/ G2333	SB	Red	Cream	Mottled
NABE18						2012								K132/NAT067	B	Purple	Cream	Mottled
NABE19						2012								Kanyebwa/ K132	B	Red	Cream	Mottled
NABE20						2012								K132/ G2333	SB	Pink	Red	Striped
NABE21						2012								Kanyebwa/ NAT003	B	Cream	Red	Mottled
NABE22						2012								K132/ NAT 067	B	Purple	Cream	Mottled
NABE23						2012								Kanyebwa/ K132	B	Pink	Red	Striped
NABE26C						2012							CIAT	MAC31/ MLB49-89A	C	Purple	Cream	Mottled
NABE29C						2012								MAC31/ MLB 49-89A	C	Red		None
Kabanimba							1979									Red	Cream	Mottled
JESCA (SOYA NDEFU)							1997								B	Purple	Cream	Speckled
A197							2002		1995		1998		CIAT	G76/ G217221	B	Cream		None
SELIAN 05							2005											
PAN150								2002					CIAT	MOC2/ BAT1647	SC	Black		None
A286								2010	1996				CIAT	G4017/ G4830	B	Cream	Others	Pinto
ZEBRA								2013					CIAT		SC	Cream	Others	Pinto
WERNA								2015					Landrace		SB	Red		None
A334									1996				CIAT	G3807/ G4017	B	Cream		None
CAL143									1996									
NUA59									2009				CIAT		B	Red	Cream	Mottled
NATAL SUGAR										1980						Cream	Pink	Striped
VTTT925/9/1-2 (SWEET VIOLET)										2013	2013	2013	CIAT	SUG135// DFA14/ CAL154	SB	Cream	Pink	Striped
A222												1995	CIAT		B	Black		None
VTTT923/103 (KALAMBO)											2011		CIAT	ANT21/ ICA CAUCAYA // AFR687/ SEQ 1003	SB	Cream	Pink	Striped
BOUNTY										2002			CIAT		B	Cream	Pink	Striped
Gloria (PC652-SS3)										2012					SB	Cream	Pink	Striped
CHERRY										2013			CIAT	Trepador//CAL143/ CAL116	B	Red	Cream	Mottled
RI5-2 (FOFIFA RAMJONOMBY)													NARS	Ranj/ Ikinimba// Ranj/ Awash	B	White		None
RI5-5 (MENAKELY)													NARS		B	White		None
ALB24													CIAT	SER16// SER16/ G353463Q	B	Red		None
CMKN1550													CIAT		C	Cream		None
DECELAYA															C	Red		None
DOR500														DOR362/ G18521// DOR365/ LM30630	B	Black		None
MIB465													CIAT	INB36/G23818B	SB	Black		None

BU = Burundi, KE = Kenya, DRC= Democratic Republic of Congo, ET = Ethiopia, RW = Rwanda, UG = Uganda, TZ = Tanzania, SW = Swaziland, MA = Malawi, MO = Mozambique, ZI = Zimbabwe, ZA = Zambia, GH = Growth habit, C = Climber, SC = Semi climber, B = Bush, SB = Semi Bush, PSC = Primary seed colour, SSC = Secondary seed colour, SCP = Seed colour pattern, CIAT = International Center for Tropical Agriculture, NARS = National Agricultural Research Stations

TABLE 2. Adjusted means and annual genetic gain from simple linear regression for yield (YDHA)

No.	Country of 1st release	Year of 1st release	Variety	YDHA
Large-seeded bush beans				
1	Tanzania	1979	Kabanimba	769.7
2	Zimbabwe	1980	Natal Sugar, Red Canadian wonder	852.0
3	Kenya	1982	GLP2, Mwetamania	947.6
4	Burundi	1987	HM21-7	829.6
5	DRC, Rwanda	1991	MLB-49-89A, URUGEZI (1378/4)	804.6
6	Uganda	1994	CAL 96	838.9
7	Malawi, Uganda	1995	A197, NABE 1	884.6
8	Kenya	1998	KAT B1, KATX69	864.1
9	Burundi, Kenya, Uganda, Ethiopia	1999	AKARYOSE (NAROBEAN3), KATX56, NABE 4, NABE 5, Speckled ice	851.3
10	DRC	2000	Ngwaku Ngwaku	934.3
11	Zimbabwe	2002	BOUNTY	762.0
12	Uganda	2003	NABE 11	978.0
13	DRC, Uganda	2006	AFR708, CODMLB 001, CODMLB 033, NABE 13, NABE 14, NAROBEAN 1 (RWR 2154), NAROBEAN 2 (RWR 2245), NUA 35, ZKA93-10M/95	1091.6
14	Ethiopia, DRC, Kenya	2007	AFR-703, MONTCALM, NUA 45, SCAM-80 CM/15	920.4
15	Burundi	2008	BISERA, KAT B9, MUSENGO	977.2
16	Malawi	2009	NUA 59	1106.0
17	Uganda	2010	NABE 15, NABE 16	970.7
18	DRC, Zambia	2011	NUA 99, VTTT 923/10-3	943.6
19	Zimbabwe, Uganda	2012	GLORIA, NABE 17, NABE 18, NABE 19, NABE 20, NABE 21, NABE 22, NABE 23	870.6
20	Zimbabwe, Malawi	2013	Cherry, Sweet violet	988.5
21	Kenya, Burundi	2017	DAB 299, RWR 1092	922.8
	Land race		Masindi yellow LONG	956.1
	Land race		Masindi yellow SHORT	967.0
	Breeding line		DAD 34	1091.0
			Simple linear regression (YDHA)	Sig. level
	Regression			0.011
	r2 (%)		25.6	
	Se_ observations		79.3	
	Y intercept		-7918	0.021

TABLE 2. Contd.

No.	Country of 1st release	Year of 1st release	Variety	YDHA
	Slope (annual gain)		4.41	0.011
	Relative annual gain over the 1st variety		0.6%	
Small-seeded bush beans				
1	Ethiopia	1973	Mexico 142	632.2
2	DRC	1986	G 2858	932.1
3	Ethiopia, DRC	1990	AWASH 1, ROBA-1	774.0
4	DRC, Rwanda	1991	RWR 362, RWR 719	855.4
5	Uganda	1994	K131 (MCM 5001)	1020.5
6	DRC, Uganda	1995	AND620, MCM 1015 (NABE 2), MCM 2001 (NABE 3)	965.2
7	Malawi	1996	A286, A344	810.4
8	Ethiopia, Tanzania, Uganda	1999	Awash melka, Kabulanketi, NABE 6	846.0
9	DRC	2002	XAN-76	1081.4
10	DRC	2003	CNF 5520, DC12496-50	1179.6
11	DRC	2006	ACC 714, M'sole	830.3
12	DRC, Ethiopia	2007	DRK 64 (NAIN DE KYONDO), VAX2	1018.0
13	Kenya, Burundi	2008	GLP 585, Mukungugu	883.2
14	Rwanda	2010	RWR 1180, SER 16	955.5
15	Mozambique, Burundi, DRC	2011	A222, Kilyugaramye, Maharage Soja	971.7
16	DRC	2013	ECAPAN 021	761.6
17	Kenya, Swaziland	2015	KAT SW-12, KAT SW-9	909.1
	Land race		Kanyebwa	1012.2
	Land race		OCUC	824.0
	Breeding line		ALB 24	1197.0
	Breeding line		BFS 27	1575.3
	Breeding line		NCB 226	1473.6
	Breeding line		SER 48	1469.3
	Breeding line		SER 82	1158.2

TABLE 2. Contd.

No.	Country of 1st release	Year of 1st release	Variety	YDHA
	Simple linear regression (YDHA)			Sig. level
	0.127			
	9.1			
	125			
	-8240			0.166
	4.57			0.127
	0.7%			
Large-seeded climbers				
1	Burundi	1987	FLOR DE MAYO	979.8
2	DRC	1991	AND10	1100.9
3	Uganda	1999	NABE 9C	1190.9
4	Uganda	2003	NABE 12C	1126.0
5	Burundi	2006	Twungurumirwango	759.9
6	Burundi, Kenya	2008	Bihogo, KK 20	1107.9
7	Rwanda, Burundi	2010	CAB 2, GASIRIDA, MAC 42, MAC 44 (NAROBEAN 4C), RWV 1129	1073.4
8	Uganda, Rwanda	2012	NABE 26C, NABE 29C, RWV 2887, RWV 3006, RWV 3316	941.3
	Check		GITANGA	694.6
	Check		NGWIN X CAB 2	684.4
	Breeding line		CMKN 1550	1163.5
			Simple linear regression (YDHA)	Sig. level
	Regression			0.669
	r2 (%)		-	
	Se_ observations		145	
	Y intercept		6513	0.612
	Slope (annual gain)		-2.74	0.669
	Relative annual gain over the 1st variety		-	0.3%

TABLE 2. Contd.

No.	Country of 1st release	Year of 1st release	Variety	YDHA
Small-seeded climbers				
1	DRC	1990	G 2333	859.7
2	Rwanda	1991	G685 (NABE 7C)	1337.9
3	Uganda	1999	NABE 10C	1315.2
4	Rwanda, Swaziland, Malawi	2002	CAB 19, PAN 150, UBR (92)25	774.4
5	TANZANIA	2005	Selian 05	1263.4
6	DRC	2006	AB136, VCB 81013	1345.8
7	DRC	2007	NAROBEAN 5C	1288.0
8	Burundi	2009	Amahunja	1792.7
	Check		B10 Zebra	777.1
	Check		DON TIMOTEO	836.9
	Simple linear regression (YDHA)			Sig. level
				0.212
	12.0			
	296			
	-41922			0.224
	21.6			0.212
	1.6%			

YDHA = yield estimated in kg ha^{-1}, sig. = significance, r^2 = percentage variance accounted for by regression, se = standard error were laid out in an alpha lattice design, with two replications. Plots representing each line within a replication were of 3 rows by 3 m in length. Row and plant spacing were 50 cm and 10 cm for bush, and 50 cm and 20 cm for climbing beans, for one seed per hill. Each trial was weeded thrice and an insecticide, Dimethoate and two fungicides (Mancozeb and Ridomil) were applied weekly until physiological maturity, to control pests and diseases; each at the recommended manufacturer's rate. Granular N:P:K 17:17:17 fertiliser was applied at planting at the rate of 125 kg ha^{-1}.

Data collection. Data for yield, diseases and other agronomic traits were collected at specific intervals based on the bean trait dictionary (IBP, 2013). Days to flowering (DF) and physiological maturity (DPM) were recorded as number of days from planting to the day when 50% of plants had at least one flower, and number of days from planting to the day when the first pods began to discolour in 50% of the plants, respectively (CIAT, 1987; IBP, 2013). Seed harvesting for yield began when 90% of the pods had discoloured. The seeds were sun-dried to 13% moisture content and sorted for foreign matter before recording total seed weight per plot.

For determination of seed iron and zinc concentration, 15 well-filled pods hanging above the soil were randomly selected from each plot and placed in clean envelops before the main harvest. The pods were hand-threshed, and a 50-g seed sample per plot was packed in new paper bags, after wiping with paper towel dipped in distilled water to remove soil contamination. The seed samples were analysed for iron and zinc concentrations using the Oxford instruments X-Supreme 8000 energy dispersive X-ray Fluorescence (XRF) model using the method described by Mukamuhirwa *et al.* (2015).

Data analysis. Data for each location were analysed separately using Resolvable Alpha Lattice design, in Breeding View standalone statistical tool (VSN International, 2017), to assess within trial variability before performing combined analysis of variance (ANOVA) in the same software. Genotype mean (BLUP- best linear unbiased prediction) data per season were used to determine stability for yield, iron and zinc concentration. Stability for yield was calculated for each genotype using Cultivar Superiority (CS). According to Lin and Binns (1988), CS is the sum of the squares of the difference between the genotypic mean in each environment and the mean of the best genotype, divided by twice the number of environments. Genotypes with the smallest values of CS tend to be more stable, and closer to the best genotype in each environment (Lin and Binns, 1988).

To estimate realised genetic gain, the trials for bush and the climbers were each separated into three product profiles: large and small seeded beans, and high iron beans. Each product profile was re-analysed separately using randomised complete block design, in breeding view (VSN International, 2017) to assess for conformity to assumptions of ANOVA and remove outliers. Trial data were then analysed using GenStat (VSN International, 2019) to obtain adjusted means in using the model represented by Equation 1:

$$Y_{ijkl} = GM+R_i/(SL_{jk})+S_j+L_k+S_jL_k+G_l+GS_{lj}+GL_{lk}+GSL_{ljk}+e_{ijkl}. \ldots\ldots\ldots\ldots \text{Equation 1}$$

Y_{ijkl} = the observed value; GM = Grand Mean; $R_i/(SL_{jk})$ = Replication effect nested within seasons and locations; Sj = Season effect; L_k = Location effect; G_l = Genotype effect; GSL_{ljk} = Genotype x Season x Location effect; and e_{ijkl} = error (Holland *et al.*, 2003).

Realised genetic gain was determined by regressing adjusted means against year of variety release, using simple linear regression in GenStat (VSN International, 2019). The Annual rate of gain was the regression coefficient (slope of the line) represented by Equation 2:

$$b = \frac{Covariance\ (xy)}{Variance\ (x)} \text{ .... Equation 2}$$

Where:

y is the mean value of each variety and *x* the year of variety release and $y = a + bx$; a = the *y* intercept) (Nehe *et al.*, 2019; Covarrubias-Pazaran, 2021).

The annual rate of gain multiplied by the number of years since the first released variety estimates the overall genetic progress (Ejigu, 2019). The relative annual gain over the oldest variety was calculated as the ratio of annual genetic gain to the mean value of oldest released variety expressed as percentage (Nehe *et al*; 2019).

RESULTS

Analysis of variance and broad sense heritability. Repeatability (H^2, heritability in the broad sense) for across environments, estimated based on best linear unbiased prediction (BLUP), ranged from 0.61 in yield (YDHA) to 0.84 in days to flowering (DF) for bush beans; and 0.26 in DPM to 0.80 in FESEED for climbers (Table 3). The genotypes were significantly different (P<0. 01) in all

TABLE 3. Across environment ANOVA for bush and climbing beans

Statistic	DF	DPM	YDHA	FESEED	ZNSEED
Bush					
Repeatability/ Heritability	0.84	0.77	0.61	0.78	0.74
Genotype Variance	7.8***	5.6***	22828.8***	26.6***	4.5***
GenxEnvt Variance	3.0***	0.0	45159.0***	9.4***	2.3***
Environment Variance	118.8***	26.6***	188802.6**	43.6***	16.2***
Residual Variance	8.5	13.4	83182.5	54.9	11.6
Grand Mean	43.3	71.7	899.0	67.4	35.3
Range	37.3-50.8	65.5-80.1	377.6-1460.9	52.5-91.7	29.0-45.2
LSD (5%)	3.4	3.4	276.4	7.3	3.3
CV (%)	6.7	5.1	32.1	11.0	9.6
n Replicates	2	2	2	2	2
n Environments	5	4	6	5	5
Climbers					
Repeatability/ Heritability	0.52	0.26	0.75	0.80	0.76
Genotype Variance	3.3**	0.9	52516.1***	38.5***	5.8***
GenxEnvt Variance	8.0***	5.7***	35824.0**	4.7	2.4*
Environment Variance	4.0**	0.0	75274.7	96.5***	27.5**
Residual Variance	2.5	3.6	141233.2	68.5	10.3
Grand Mean	46.7	89.5	1050.9	68.7	34.1
Range	43.1-53.9	86.0-94.1	549.2-1551.7	57.8-86.7	29.2-43.3
LSD (5%)	3.7	2.3	350.5	8.8	3.7
CV (%)	3.4	2.1	35.8	12.0	9.4
n Replicates	2	2	2	2	2
n Environments	3	3	6	4	4

DF = days to 50% flowering, DPM = days to 50% physiological maturity, YDHA = yield estimated in kg/ha, FESEED = seed iron (ppm), ZNSEED = seed zinc (ppm), LSD = least significant difference, CV = coefficient of variation, Envt = environment, n = number, GenxEnvt = genotype by environment interaction traits, except in DPM for climbers. For the different product profiles, H^2 for individual trials were mostly moderate to high (Table 4). Due to low repeatability one trial (Kag18B) with H^2 of < 0.2 for ZNSEED was excluded from the combined analysis for the trait when genotypes were separated into product files. For each product profile, genotypes were significantly ($P < 0.001$) different in all traits (Table 4).

Genetic gain in yield and seed iron concentration. The variances accounted (r^2) for by the regression of adjusted means against year of variety release, were weak ranging from 4.3 to 25.6%; and the regression, slope and y intercept were only significant ($P<0.01$) for the large-seeded bush beans (Tables 2, 5). Annually realised genetic gain for yield was 4.41 kg ha^{-1} (slope "b") for large-seeded bush beans (Fig. 1A), which represented a gain of 167.6 kg ha^{-1} for 38 years (1979 to 2017). The relative genetic gain in YDHA (percent increment over the oldest released variety, Kabanimba) was 0.6% kg ha^{-1} per year (Table 2). The highest realised annual gain in yield of 21.6 kg ha^{-1} was recorded in small-seeded climbers; however, the regression was not significant ($P=0.2$) (Table 2). On the other hand, the large-seeded climbers had a negative slope ($b = -2.74$) for yield, indicating a slight penalty. The gain over yield checks CAL96 and Awash1 for bush beans, and Gitanga and Don Timoteo for climbers, calculated per year of release, showed no consecutive progress in the years of release (Fig. 2). Up to 30, 52, 71 and 114% increments in yield above the checks for large and small seeded bush beans, and small and large seeded climbers, respectively, were realised in different years (Fig. 2).

For high iron beans (HIB), the annual genetic gain was 0.40 ppm (0.6% of yearly increment over the oldest released variety, AWASH1); and 0.17 ppm (0.2% over AND10) for FESEED in bush (Fig. 1B) and climbers, respectively (Table 5). Considering the generation of variety release, means of 64.2, 73.8 and 71.9 ppm for fast track, second and third generations were recorded for bush beans, and 69.3 and 72.7 ppm for climbers for fast track and second generation (Table 5). The high iron check genotypes for bush (MIB465) and climbing (decelaya) beans had 60.2 and 64.3 ppm of FESEED, respectively. While the highest mean increment was obtained in the second generation of bush beans, notable differences between the mean of each generation and the checks were realised.

Genotype performance. Across environments, DF and DPM for the bush beans ranged from 37 to 51, and 66 to 80 days, respectively (Table 3). On average, genotypes flowered in 43 days and reached physiological maturity in 72 days (Table 3). Yield performance ranged from 377.6 - 1460.9 kg ha^{-1}; while FESEED and ZNSEED ranged from 52.5 to 91.7 and 29.0 to 45.2 ppm, respectively (Table 3). The average performance of genotypes in yield, FESEED, ZNSEED were 899.0 kg ha^{-1}, 67.4 ppm and 35.3 ppm, respectively (Table 3). In consideration of different product profiles, large seeded bush beans (916.5 kg ha^{-1}) had higher across environments performance; whereas small seeded bush beans (896.8 kg ha^{-1}) had lower performance (Table 4) compared to the combined means. Genotypes NCB266, BFS27 and SER48 were the most stable and superior in yield; while UBR (91)45-1 was the best in FESEED and ZNSEED; followed by Nain DE Kyondo for iron and sweet violet for zinc (Table 6).

Five genotypes (CAL143, ALB24, RWR2245, VAX5 and SEA15) were among the 20 most stable and superior genotypes in YDHA, FESEED and ZNSEED. Ten genotypes combined stability and superiority for FESEED and ZNSEED (Table 2). Correlation analysis revealed significant positive moderate association between iron and zinc [r=0.69***], and DF and DPM [r=0.49***] (Table 7). The

TABLE 4. Repeatability (Broad sense heritability) for each trial analysed within product profiles

Environment	FESEED	ZNSEED	FESEED	ZNSEED	YDHA			
	HIB bush		HIB climbers		LargeSB	LargeSC	SmallSB	smallSC
Repeatability/ Heritability								
Kac17B					0.84	0.30	0.75	0.63
Kac18A	0.66	0.82	0.64	0.81	0.51	0.46	0.69	0.70
Kag17B	0.66	0.55			0.74	0.95	0.66	0.46
Kag18A	0.53	0.15	0.71	0.55	0.54	0.62	0.75	0.61
Kaw17B	0.78	0.55	0.61	0.86	0.48	0.42	0.57	0.53
Kaw18A	0.70	0.63	0.76	0.72	0.57	0.58	0.60	0.87
Repeatability across Env't	0.87	0.79	0.79	0.84	0.50	0.71	0.64	0.79
Genotype Variance	41.7***	6.8***	38.1***	8.6***	15244***	50440***	28657***	64525***
GenxLoc Variance	3.8	2.9*	0.0	2.6*	41580***	34990*	43344***	14313
Environment Variance	44.0***	18.7***	140.0**	29.4**	189774**	57586	204482**	110576
Residual Variance	53.5	12.8	82.2	7.5	96695.9	138446	103905	179672
Grand mean	68.8	35.1	72.7	35.2	916.5	938.4	896.8	1118
Range	45.3-71.9	27.0-35.1	60.4-87.3	31.7-43.4	519-1365	416-1363	397-1496	653-1544
LSD	7.1	3.6	8.9	3.7	243.2	360.9	285.0	358
CV	10.6	10.2	12.5	7.8	33.9	39.7	35.9	38
n Replicates	2	2	2.0	2.0	2	2	2	2
n Environments	5	5	4.0	4.0	6	5	6	6

Kac = Kachwekano, Kag = Kagera, Kaw = Kawanda, 17A/18B = first/ second season of 2017 and 2018, FESEED = seed iron, ZNSEED = seed zinc, HIB = high iron beans, SB = seed bush, SC = seeded climbers

TABLE 5. Adjusted means and annual genetic gain from simple linear regression for seed iron concentration (FESEED)

No.	Country of 1st release	Year of 1st release	Variety	FESEED	FESEED	Generation	Generation means
High Iron Beans (HIB) - Bush type							
1	Ethiopia	1990	AWASH 1	62.6	62.6	Fast track	64.2
2	DRC	1991	MLB-49-89A	71.6	71.6	“	
3	Uganda	1994	K131 (MCM 5001)	58.4	58.4	“	
4	DRC	1995	AND620	65.6	66.0	“	
5	Uganda	1995	NABE 3 (MCM 2001)	66.5		“	
6	Tanzania	1997	JESCA	54.0	54.0	“	
7	Burundi	1999	Akaryose (NAROBEA3)	68.7	71.4	“	
8	Ethiopia	1999	Awash melka	66.4		“	
9	Ethiopia	1999	Speckled ice	79.1		Second generation	73.8
10	DRC	2000	Ngwaku Ngwaku	52.5	52.5	Fast track	
11	DRC	2006	ACC 714	75.5	72.0	“	
12	DRC	2006	CODMLB 001	63.8		Second generation	
13	DRC	2006	CODMLB 033	68.6		“	
14	DRC	2006	RWR 2154 (NAROBEAN 1)	76.2		“	
15	DRC	2006	RWR 2245 (NAROBEAN 2)	77.8		“	
17	DRC	2006	NUA 35	69.9		Third generation	
18	DRC	2007	NUA 45	64.0	64.0	“	71.9
19	Malawi	2009	NUA 59	75.6	75.6	“	
20	DRC	2011	NUA 99	76.0	73.1	“	
21	Malawi	2013	Sweet violet	80.9	75.6	Second generation	
22	Zimbabwe	2013	Cherry	70.3		“	
	Fe Check		MIB465	60.2			
					Simple linear regression (FESEED)		Sig. level
	Regression						0.874
	r2 (%)				8.5		
	Se_observations				7.34		
	Y intercept				-725		0.962
	Slope (annual gain)				0.395		0.874
	Relative annual gain over the 1st variety				0.6%		

TABLE 5. Contd.

No.	Country of 1st release	Year of 1st release	Variety	FESEED	FESEED	Generation	Generation means
High Iron Beans (HIB) - Climbers							
1	DRC	1991	AND10	67.4	67.4	Fast track	69.3
2	Rwanda	2002	CAB 19	73.6	73.6	Second generation	
3	DRC	2006	VCB 81013	71.7	71.7	Fast track	
4	DRC	2007	Nyiramuhondo (NAROBEAN 5C)	70.1	70.1	Second generation	72.7
5	Rwanda	2010	CAB 2	71.0	72.5	“	
6	Burundi	2010	GASIRIDA	69.8		“	
7	Rwanda	2010	MAC 42	69.0		“	
8	Rwanda	2010	MAC 44 (NAROBEAN 4C)	72.2		“	
9	Rwanda	2010	RWV1129 (Selian15)	80.7		“	
10	Rwanda	2012	RWV 2887	67.7	75.7	“	
11	Rwanda	2012	RWV 3006	81.3		“	
12	Rwanda	2012	RWV 3316	78.0		“	
13	Swaziland	2013	Zebra	68.8	68.8	Fast track	
	Fe check		Decelaya	64.3			
					Simple linear regression (FESEED)		Sig. level
	Regression						0.311
	r2 (%)					4.3	
	Se_observations					2.75	
	Y intercept					-264	0.415
	Slope (annual gain)					0.167	0.311
	Relative annual gain over the 1st variety					0.2%	

FESEED = seed iron concentration (ppm), ZNSEED = seed zinc concentration (ppm), sig. = significance, r^2 = percentage variance accounted for by regression, se = standard error

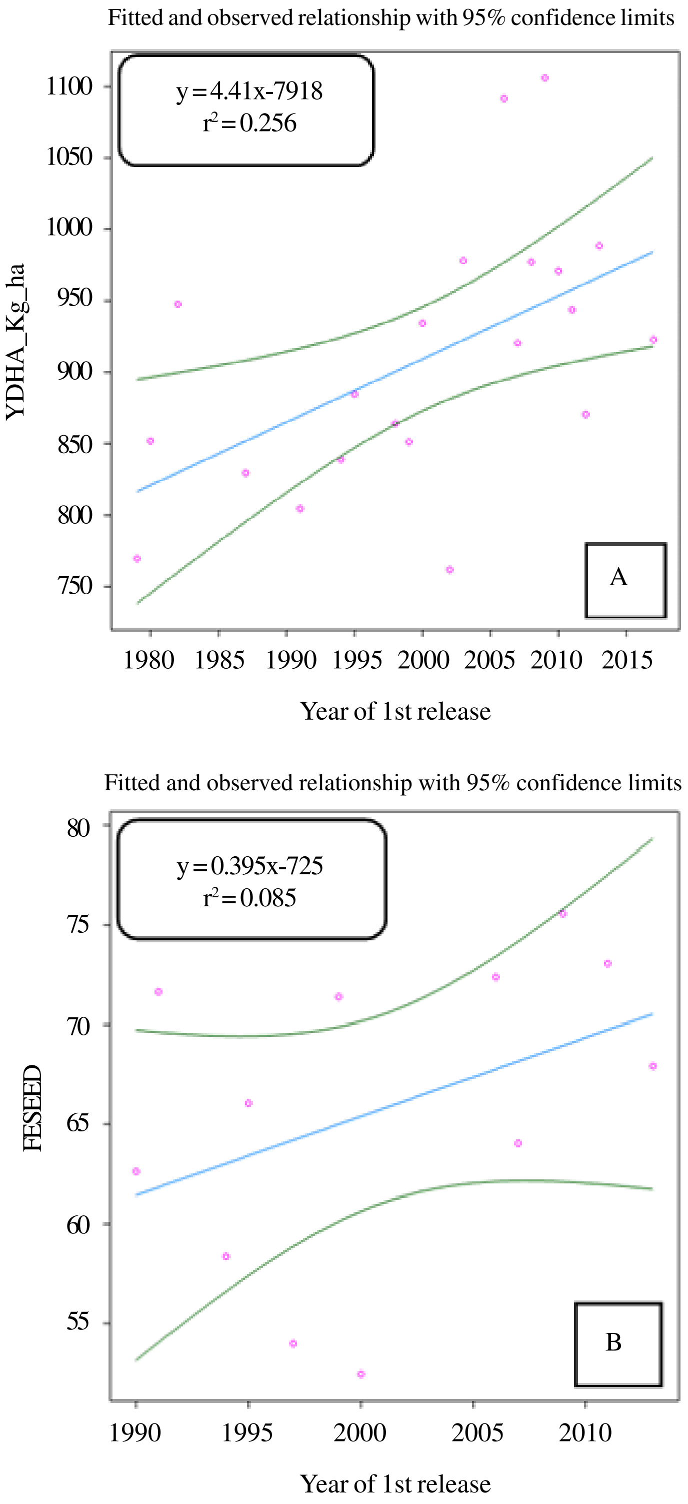

Figure 1. Simple linear regression for yield for large-seeded bush beans (A) and high iron bush beans (B).

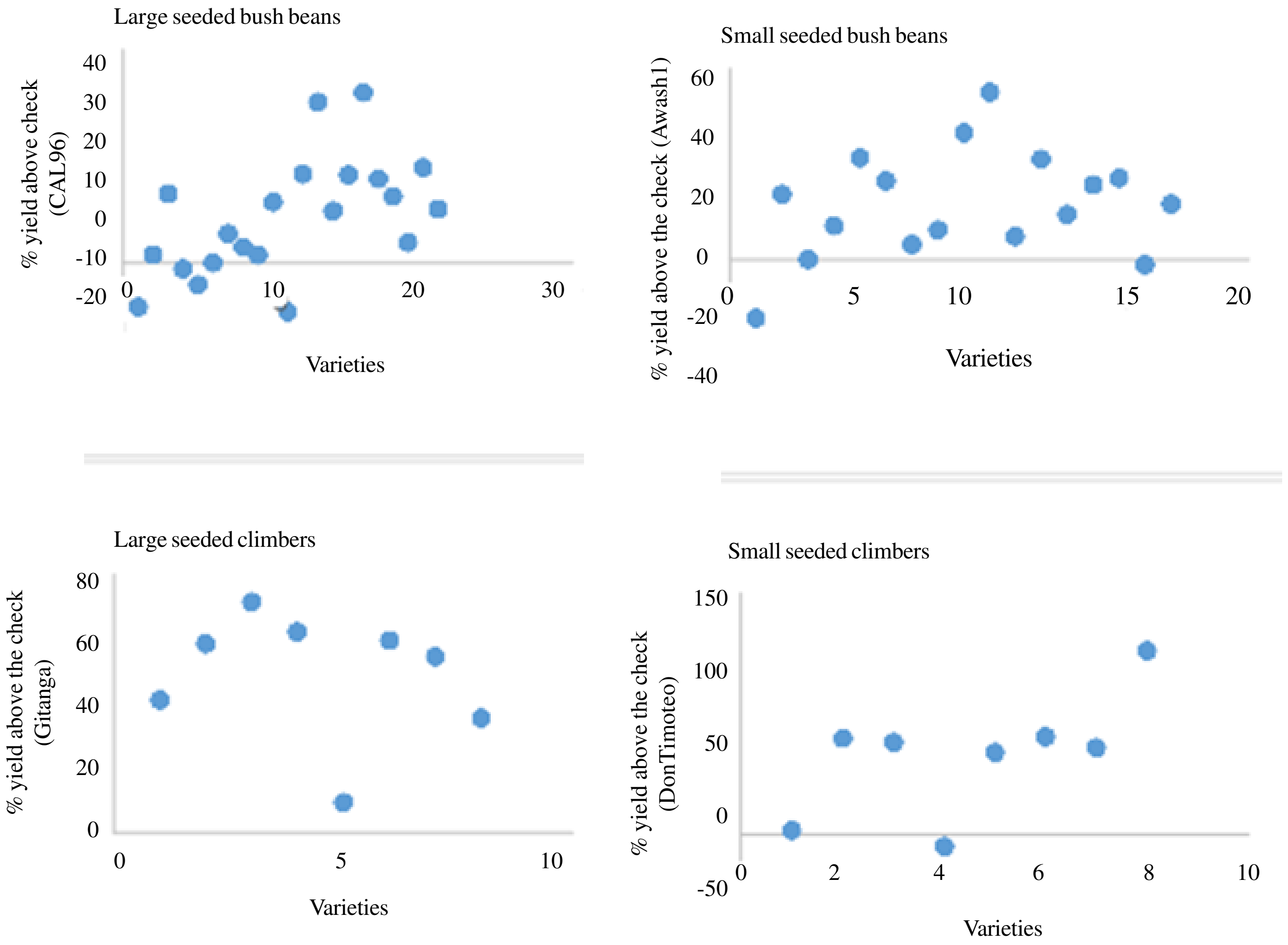

Figure 2. Percentage yield above the check genotype for the four product profiles.

TABLE 6. Stability superiority measure coefficients for bush and climbing beans

Genotype	CS	YDHA	Genotypes	CS	FESEED (ppm)	Genotypes	CS	ZNSEED (ppm)
Bush bean								
NCB 226	27735	1227	UBR(91)45-1	6	81	UBR(91)45-1	0	41
BFS 27	29052	1233	NAIN DE KYONDO	20	75	SWEET VIOLET	1	40
SER 48	52902	1137	SAB 629	21	75	SPECKLED ICE	2	39
NAROBEAN 1	52936	1154	SPECKLED ICE	28	74	NABE 22	3	38
RWR 2154	53236	1166	CAL 123	29	73	GLP2	4	38
BISERA	58438	1106	NABE 22	32	73	VTTT 923/10-3	5	38
DC12496-50	58945	1120	DRK 64	35	73	SAB 629	6	38
NABE 13	69564	1092	SWEET VIOLET	37	73	NATAL SUGAR	6	38
CAL 143	73671	1100	ACC 714	38	72	CNF 5520	6	38
ALB 24	76418	1102	NAROBEAN 2	40	72	WERNA	7	37
SER 82	79711	1033	NATAL SUGAR	42	72	DRK 64	8	37
VAX3	93828	1053	A344	44	71	GLORIA	9	38
NABE 14	94330	1113	G 21212	45	72	NAROBEAN 2	9	37
RWR 2245	100426	1046	EKKO 1	47	71	RAZ 11-1	9	37
NUA 8	102724	1051	RWR 2245	48	71	ECAPAN 021	9	37
SER 16	103710	1054	CAL 143	49	72	ALB 24	10	36
VAX5	105915	1008	SCAM-80 CM/15	50	71	Nain DE Kyondo	10	37
MIB 465	106306	1034	CODMLB 033	51	72	SCAM-80 CM/15	10	38
SEA 15	106772	1006	USCR 7	51	71	SEA 15	10	38
VAX1	106910	1121	NUA 59	52	72	VAX5	12	37
Climbing bean								
NABE 7C	13017	1331	GITANGA	1	79	GUARNTINO	2	38
SELIAN 05	19026	1299	RWV 3316	22	74	RWV 3006	2	39
VCB 81013	29655	1238	RWV1129	28	75	RWV 3316	3	38
AMAHUNJA	44951	1333	RWV 3006	31	75	NABE 29C	4	37
KK 20	51595	1231	NABE 29C	36	75	CAB 2	10	36

TABLE 6. Contd.

Genotype	CS	YDHA	Genotypes	CS	FESEED (ppm)	Genotypes	CS	ZNSEED (ppm)
NAROBEAN 5C	53929	1219	GUARNTINO	39	76	GITANGA	12	35
AB136	62809	1130	NGWIN X CAB 2	50	71	NGWIN X CAB 2	14	35
NAKAJA	65128	1191	NAKAJA	52	74	VCB 81013	14	35
DECELAYA	70666	1189	CMKN 1550	61	70	NAKAJA	15	35
FLOR DE MAYO	74797	1095	CAB 19	62	70	CMKN 1550	16	35
MEXICO 54	77279	1130	NAROBEAN 4C	66	71	NABE 26C	16	34
NABE 10C	79255	1187	NAROBEAN 5C	70	70	RWV1129	17	35
CMKN 1550	81559	1169	CAB 2	70	71	DON TIMOTEO	17	34
MAC 44	84194	1156	NABE 26C	78	69	AMAHUNJA	18	35
G685	88477	1134	ZEBRA	82	69	AND10	19	35
CAB 2	95231	1142	NABE 12C	90	70	BIHOGO	19	34
GUARNTINO	96979	1080	MAC 42	91	69	USWK 6	21	34
RWV1129	110208	1165	GASIRIDA	97	69	MEXICO 54	21	34
NABE 12C	114117	1097	BIHOGO	102	68	PAN 150	22	34
NAROBEAN 4C	117273	1041	VCB 81013	104	70	MAC 42	22	34

CS = cultivar superiority, genotypes with smaller values are more stable, YDHA = yield in kg ha^{-1}, FESEED = seed iron concentration (ppm), ZNSEED = seed zinc concentration (ppm)

TABLE 7. Association of between iron, zinc, yield, days for flowering and maturity

	FESEED	ZNSEED	YDHA	DF
Bush beans				
FESEED	-			
ZNSEED	0.69***	-		
YDHA	0.08*	0.29***	-	
DF	0.02	0.07	0.05	-
DPM	-0.11**	0.02	-0.05	0.49***
Climbing beans				
FESEED	-			
ZNSEED	0.57***	-		
YDHA	0.00	0.09	-	
DF	0.33***	-0.17	-0.26**	-
DPM	0.32***	-0.28**	-0.19*	0.83***

Number of observations = 714 and 124 for bush and climbing beans respectively, FESEED = seed iron concentration (ppm), ZNSEED = seed zinc concentration (ppm), YDHA = yield (kg ha^{-1}), DF = days to 50% flowering, DPM = days to 50% physiological maturity

association of both iron and zinc to yield was weak, but positive (Table 7).

For the climbing beans, across environment mean performance was 47 days, 90 days, 1050.9 kg ha^{-1}, 68.7 ppm, and 34.1 ppm, for DF, DPM, YDHA, FESEED and ZNSEED, respectively (Table 3). In consideration of different product profiles, large seeded (938.4 kg ha^{-1}) climbing beans had lower mean performance across environments (Table 4). One the other hand, the small seeded ones (1118.0 kg ha^{-1}) had higher mean performance across environments (Table 4), compared to the combined means. In addition, higher mean of 72.7 ppm for high iron beans was recorded (Table 4). Genotypes NABE 7C, SELIAN 05 and VCB 81013 combined stability and superiority in yield; while six genotypes (CAB 2, CMKN 1550, GUARNTINO, NAKAJA, RWV 1129 and VCB8 1013) were among the 20 stable and superior genotypes in the three traits. Fourteen varieties combined stability and superiority for FESEED and ZNSEED (Table 6). Correlation analysis revealed significant positive moderate to high association between iron and zinc [r=0.57***], and DF and DPM [r=0.83***] (Table 7). No association existed between iron and yield, and a very weak one existed between zinc and yield (Table 7).

DISCUSSION

Genetic gain in yield and seed iron concentrations. Overall, progress in genetic improvement was evident for most product profiles, although it was generally slow (Tables 2 and 5). This was expected because the varieties were released in different countries that used different check varieties in evaluations. The lack of standard references below which genotypes would not be selected for promotion implied that varieties released in the same year were not necessary superior across PABRA but within a country. In addition, some varieties were released in multiple countries with huge gaps (10+) between years of variety release (Table 1); which indicated that not all breeding programmes were at the same level and that newer genotypes were not being widely evaluated and promoted. Also, some genotypes were released for specific adaptation, which made the environments used in this study not the most suitable for their expression. The use of target population of environments (TPEs), which are still being characterised in PABRA, is expected to improve genotype testing strategies and consequently genetic gain estimation using historic data set.

Genetic gain may be better reflected within than across countries; but due to the few varieties and gaps in years of varietal release in some countries, such as Uganda and the Democratic Republic of Congo (DRC), this was not estimated. Significant gain was obtained in large-seeded bush beans probably because approximately half of the studied varieties belonged to this profile, suggesting more breeding efforts directed to their improvement as they are preferred in many African countries. Although not significant (P>0.05), all the other product profiles showed genetic gain in yield, except large-seeded climbers where mean yields varied in countries where climbers are mostly grown (e.g., Burundi 886.2 kg ha^{-1}, Rwanda 968.0 kg ha^{-1} and Uganda 1,199.6 kg ha^{-1}) point to varying yield targets for new varieties.

Earlier studies in Uganda, Ethiopia and Brazil showed relative genetic gain in yields of 1.3 to 6.7% per year for common beans (Bezaweletaw *et al*., 2006; Barili *et al*., 2016; Mukayiranga, 2016); with the highest gain reported in Brazil. This shows that higher genetic gain in common bean yield is achievable. However, thoughtful consideration of several factors, such as breeding and selection methods, focus of the breeding programme and stability of genotypes is necessary (Ponte *et al*., 2016). Relative gain of 0.6-1.6% per year recorded in yield in different product profiles in this study reflected progress through breeding efforts in PABRA. Chiorato *et al.* (2010) reported genetic gain in yield of 1.07% per year in Brazil in the first period (1989-1996), with zero genetic gain in the second period (1997-2007). The authors noted that despite the no genetic gain, there was better grain quality in the evaluated lines in the second period, more than in the first one because the focus in the programme during that period was on grain quality.

The significant gain in yield of large seeded bush beans reported in the present study, could be explained by the focus of breeding programmes towards this product profile. Large seeded beans are the most preferred in eastern Africa and is thus a major breeding focus in this area (Farrow and Muthoni, 2020). Involvement of strong parameters such as cycle time for increasing genetic gain, as a model for expected change in trait in response to selection in the breeder's equation is said to be crucial (Cazzola *et al*., 2021). Although realised genetic gain was estimated in the present study, the gaps in years of release of the same variety in multiple countries, or even variety release within a country showed that the efficient use of cycle time in the breeders' equation could result into quicker and better products.

Speedy breeding, an emerging technology, allows increased efficiency of the programmes, thereby reducing time, costs and the work required (Cazzola *et al*., 2021). Rapid development of homozygous lines is achievable through optimal environmental conditions that accelerate photosynthesis and flowering to cause early seed harvest (Cazzola *et al.* (2021). Such technologies include the use of photoperiodism, temperature regulation, plant density, soil moisture, carbon dioxide levels, nutrition and hormones strategies (Wanga *et al*., 2021). Speedy breeding can be integrated with other technologies such as marker assisted selection and high-throughput phenotyping methodologies that shorten the breeding cycle and increase genetic gain per unit time (Wanga *et al*., 2021).

The criteria for selection of superior genotypes also influence genetic gain (Bezaweletaw *et al*., 2006; Wanga *et al*., 2021). Multiple trait selection for yield related traits and actual yield, in addition to other important traits, with an inclusive focus of selection of top performing genotypes while maintaining genetic diversity in the breeding population is important for genetic gain (Falk, 2010; Bezaweletaw *et al.*, 2006). Another selection component of kin interest is the use of uniform checks across regional trials to ensure that lines that are consistently better than the checks are selected. This practice is expected to buffer the varying trait targets within countries to enable progressive selection of better genotypes in PABRA. Earlier studies report gains in yield of common bean of 60.4-82.4% over the local checks (Bezaweletaw *et al.*, 2006; Barili *et al.*, 2016; Mukayiranga, 2016). These are comparable to gains reflected in some years over checks CAL96, AWASH1, Gitanga and DonTimoteo. However, inconsistent incremental performance of varieties above the checks was notable. A uniform check strategy to provide standard references is important for progressive genetic gain in routine regional trials evaluation.

The year of varietal release was also reported to influence genetic gain (Kefelegn *et al.*, 2020). A notable practice is the release of multiple genotypes for the same market in the same year (Kefelegn *et al.*, 2020). Updated product profiles and a clear variety replacement strategy are tools for market-oriented and impactful breeding (Ragot *et al.*, 2018; Singh *et al.*, 2019). These are useful tools that are being promoted to bridge the gap between variety release, which was notable with countries in PABRA.

The nonsignificant gain in FESEED could have been due to few (four) third-generation bush beans and no climber, which mirror a limited number of the third-generation varieties released by 2017. The fast-track varieties evolved from the first study of regionally grown varieties in Africa; while the second and third generations refer to genotypes developed from targeted crossing programmes aimed at increasing FESEES levels to >90 ppm. When the progress was compared to the performance of the high iron bush bean check genotype (MIB465) commonly used in PABRA, 4.0, 13.6 and 11.7 ppm of FESEED were realised above the check (60.2 ppm) for the first track, second and third generation, respectively. Considering varieties, only sweet violet, a second-generation variety expressed >20 ppm above the check (Table 5). Nonetheless, 47.8% of the varieties concentrated 10+ ppm of FESEED above MIB465; indicating some progress in the varieties in the hands of farmers. For the climbers, 8.9 and 12.2 ppm of FESEED for the first track and second generation were obtained above the 64.3 ppm in Decelaya, the check, and an increment of >20 ppm above Decelaya, was attained in the second-generation varieties; RWV1129 (Selian15) and RWV 3006. A study involving more third generation varieties may show better progress in improvement for FESEED; but also, the study showed that countries were releasing different generations in the same year which presents a challenge in estimating genetic gain across countries as the latest generation varieties should possess higher FESEED. Increments of 0.6 and 0.2% per year for FESEED over the first released bush and climbing bean variety showed a slow genetic progress in both groups. Nonetheless, HIB with 20 ppm of FESEED above local checks exist (Beebe, 2020). The study reflects that majority of these genotypes were not yet in the hands of farmers in Africa by around 2017.

Improvement in common bean FESEED and ZNSEED in PABRA was initiated in 1996 by the collection and phenotyping of regionally grown materials (Amongi *et al.*, 2018). This led to the identification of genotypes with > 70 ppm of FESEED that were regionally promoted as high iron beans. Targeted breeding has since resulted in the release of several high iron beans (Mulambu, *et al.*, 2017). However, genotype by environment interaction was reported as a factor influencing iron concentration in a variety (Martins *et al.*, 2016). A more reflective genetic gain could be estimated by first defining the target population of environments (TPEs) such as sets of farms in which the varieties produced by a breeding program would be grown.

Yield, and seed iron and zinc concentration. Repeatability in all traits were generally high, which indicated that the genetic attributes of the genotypes were captured. Genotype variance indicated high diversity in yield that could be exploited for breeding. Limited diversity was expressed in days to flowering and maturity which was reflective of the tendency of breeders and the farmers to select for similarity in these traits. In terms of FESEED and ZNSEED, less diversity than yield was also reflected especially in the bush types as a slightly higher genotype variances were expressed in the climbing beans.

The top three (NCB226, BFS27 and SER48) most superior and stable bush bean genotypes in yield were all new breeding lines and this pointed to better yielding lines in the breeding pipeline. Nonetheless, the top 20 genotypes also consisted of both recently released and old varieties, with some of them like RWR2154, RWR2245, MAC44, RWV1129 that have been released regionally although in different years.

The weak association between yield and iron and zinc observed in the study (Table 7) has also been reported in several earlier studies (Ribeiro *et al*., 2013; Amongi *et al*., 2018); suggesting unlikely yield penalty during breeding. This was reflected in 11 varieties that combined superiority and consistency across environments for yield, iron and zinc that appeared among the top 20 bush or climbers (Table 2). Nonetheless, careful selection criteria need to be implemented during breeding since several quantitative trait loci (QTL) for negative yield components colocalise with those for increased FESEED and ZNSEED, despite the existence of favourable independent QTL for these traits (Diaz *et al*., 2022).

CONCLUSION

There is evidence of genetic improvement among common bean genotypes released under the Pan African Bean Research Alliance (PABRA) in Africa from 1973 to 2017; although the realised annual gain is only significant in large seed bush beans. Regionally used uniform checks as benchmarks are important for consistency in genetic gain assessment across countries. To address the inconsistency caused by the gap between variety release, a clear variety replacement strategy is expected to result in quicker release of a variety in multiple countries within the same time. Breeding lines that are superior in yield over all the varieties show the existence of potential varieties for release in the breeding pipeline which is quite promising. However, third generation high iron beans (HIB) are not reflected much among released varieties by 2017 which showed a gap in variety replacement. A genetic gain assessment including more third generation HIB is recommended to provide a better representation.

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