Table S1A: Parental inbred lines used in the factorial mating scheme

Inbred No.	Pedigree	Group[1]	Description
1	9450xKI21-1-5-3-2-2-B/DE3/9450xKI21-1-5-3-2-2-B-32-B*6	I	High Zn and High PVA
2	(9450xKI21-1-5-2-1-2-B/DE3/9450xKI21-1-5-2-1-2-B)-16-B*5	I	High Zn and High PVA
3	9450xKI21-1-5-3-2-2-B/DE3/9450xKI21-1-5-3-2-2-B-23-B*6	I	High Zn and High PVA
4	4205/DE3/4205-20-B*7	1	High Zn and High PVA
5	(9450/CM116/9450)-3-3-1-2-1-B*7/9450/KI21-1-5-3-2-2-B/DE3/9450/KI21-1-5-3-2-2-B-30-BB-19-B-2-B-B-1	II	High Zn and High PVA
6	(9450/CM116/9450)-3-3-1-2-1-B*7/9450/KI21-1-5-3-2-2-B/DE3/9450/KI21-1-5-3-2-2-B-30-BB-8-B-1-B	II	High Zn and High PVA
7	4205/DE3/4205-16-B*8	II	High Zn and High PVA
8	(ACR97TZL-CCOMP1-Y-S3-13-1-BB/CI7/ACR97TZL-CCOMP1-Y-S3-13-1-BB)-8-B*5	II	High Zn and High PVA
9	ATPS7-24y-B/4001/B73LPA/4001-9-2-1-B*4-21-B-1-B-1	III	High Zn and Low PVA
10	CamI9P117-B*4	III	High Zn and Low PVA
11	KU1414xCM117-1xKU1414-7-2-B*12	III	High Zn and Low PVA
12	ATPS7-24y-B/4001/B73LPA/4001-9-2-1-B*4-26-B-1-B-1	III	High Zn and Low PVA
13	(IYFCO-22-2-2)-B-2	IV	Low Zn and Low PVA
14	4205/DE3/4205-16-B*8	IV	Low Zn and Low PVA
15	(9450xCM116x9450)-5-1-3-1-B*7	IV	Low Zn and Low PVA
16	KU1409xMO17LPAxKU1409-27-3-1-1-BB/(CIM116xTZMi302xCIM116)-2-2-B*8-15-B*4	IV	Low Zn and Low PVA
17	(IYFCO-93-3-1)-B-1	V	Low Zn & Fe and High PVA
18	IYFCO-10-2-1-1-1	V	Low Zn & Fe and High PVA
19	IYFCO-20-1-1-3-3	V	Low Zn & Fe and High PVA
20	(KU1409/DE3/KU1409) S2-2-B*7	V	Low Zn & Fe and High PVA
21	(IYFCO-193-2-2)-B-2	VI	Low Zn and Medium PVA
22	(9450/CM116/9450)-3-3-1-2-1-B*7/9450/KI21-1-5-3-2-2-B/DE3/9450/KI21-1-5-3-2-2-B-30-BB-3-B-1-B	VI	Low Zn andMedium PVA
23	(KU1409/DE3/KU1409) S2-18-2-BBB/(KU1409/SC55/KU1409)-S2-19-1-BBB-8-B-1-B-B-1	VI	Low Zn and Medium PVA
24	4013-B/4001/KI21-3-2-1-1-1-1-B*4-6-B-1-B-1	VI	Low Zn and Medium PVA

Group [1] number referring to groups each containing four sets of lines

PVA: Provitamin A

Table S1B. Description of crossing scheme for each mating set used to generate hybrids

Mating Sets	Description	No. of hybrids
1	GI X GIII	16
II	GIII X GII	16
III	GV X GI	16
IV	GIV X GVI	16
V	GII X GIV	16
V1	GVI X GV	16

G: groups, see Table S1 for description of groups

Table S2. Means squares from analysis of variance for grainZn, Fe and PVA concentrations of 24 parental lines across environments.

Source	DF	Zn (mg kg^{-1})	Fe (mg kg^{-1})	PVA(μg g^{-1})
Env	3	47.67 **	73.53**	23.87**
Rep (Env)	4	6.55	1.16	2.46*
Block (Env*Rep)	40	7.35	3.77	0.60
Lines	23	66.47**	32.19**	34.59**
Env*Lines	69	0.13	6.86**	2.31**
Error	52	5.51	129.39	0.90
R^2		0.94	0.93	0.98
CV%		7.00	7.12	11.77
Heritability		0.94	0.80	0.96

*: significant at $p < 0.05$, ** :significant at $p < 0.01$, PVA: provitamin A, Env: environment, Rep: replication
CV%: coefficient of variation in %, R^2 %: percentage of variation explained, DF: degree of freedom

Table S3. Estimates of Specific Combining Ability (SCA) effects for micronutrients and grain yield in 96 hybrids evaluated across environments

S/N	Hybrid	Set	PVA μg g^{-1}	Fe mg kg^{-1}	Zn mg kg^{-1}	GY t ha^{-1}
1	1 x 9	I	-0.38	-0.26	0.10	0.03
2	2 x 9	I	-0.46	0.01	0.13	0.03
3	3 x 9	I	0.65*	0.04	0.77	-0.02
4	4 x 9	I	0.13	0.19	0.65	0.02
5	1 x10	I	-0.34	-0.43	-0.04	-0.01
6	2 x10	I	0.73*	1.16*	1.38*	-0.12
7	3 x10	I	-0.21	-0.66	-0.94	0.01
8	4x 10	I	-0.27	-0.17	0.17	0.07
9	1 x 11	I	0.23	1.33*	0.69	-0.03
10	2 x 11	I	-0.28	-0.39	0.31	0.02
11	3 x 11	I	-0.19	0.30	0.25	-0.08
12	4 x 11	I	0.11	-0.32	-0.54	0.01
13	1 x 12	I	0.36	0.59	1.01*	0.02
14	2 x 12	I	-0.03	-0.84*	-2.44**	0.02
15	3 x 12	I	-0.36	0.17	-0.01	0.04
16	4 x 12	I	0.07	0.05	1.19*	-0.04
17	9 x 5	II	-0.14	0.29	0.46	0.03
18	10 x 5	II	-0.22	-0.55	-0.59	0.00
19	11 x 5	II	-0.04	0.13	0.36	-0.04
20	12 x 5	II	0.18	0.51	0.17	0.02
21	9 x 6	II	-0.11	0.47	0.87	0.00
22	10 x 6	II	0.42	-0.39	0.28	0.02
23	11 x 6	II	-0.51	0.15	-0.54	-0.03
24	12 x 6	II	0.43	-0.02	1.07*	0.01
25	9 x 7	II	0.45	-0.31	0.22	0.00

Table S3 contd.

S/N	Hybrid	Set	PVA μg g^{-1}	Fe mg kg^{-1}	Zn mg kg^{-1}	GY t ha^{-1}
26	10 x 7	II	-0.34	0.58	0.54	0.00
27	11 x 7	II	-0.17	0.02	0.53	-0.01
28	12 x 7	II	0.01	-0.12	-0.01	0.00
29	9 x 8	II	-0.23	-0.49	-0.63	0.04
30	10 x 8	II	0.06	0.01	0.52	0.00
31	11 x 8	II	0.63	0.38	0.62	0.05
32	12 x 8	II	-0.54	-0.56	-0.71	0.04
33	17 x 1	III	0.52	0.39	-0.09	-0.03
34	18 x 1	III	-0.01	0.72	1.01*	0.03
35	19 x 1	III	0.24	0.75	0.35	-0.01
36	20 x 1	III	-0.85*	-1.20*	-0.07	0.04
37	17 x 2	III	-0.13	0.56	-0.97	-0.03
38	18 x 2	III	-0.47	-0.45	-0.43	0.03
39	19 x 2	III	0.30	-0.20	-0.25	0.03
40	20 x 2	III	0.36	-0.30	-0.30	-0.01
41	17 x 3	III	-0.52	-0.79*	1.61*	0.03
42	18 x 3	III	0.91*	-0.41	-1.52*	0.05
43	19 x 3	III	-0.54	0.02	-0.81	-0.05
44	20 x 3	III	0.18	0.66	-0.65	-0.07
45	17 x 4	III	-0.01	-0.16	-0.82	0.00
46	18 x 4	III	-0.51	-0.25	0.19	0.01
47	19 x 4	III	0.32	-0.40	0.19	0.06
48	20 x 4	III	0.34	0.36	0.18	-0.03
49	13 x 21	IV	-0.22	-0.25	0.10	-0.04
50	14 x 21	IV	-0.48	-0.15	-0.38	-0.01
51	15 x 21	IV	0.23	0.53	0.66	0.02

Table S3 Contd.

S/N	Hybrid	Set	PVA $\mu g\ g^{-1}$	Fe $mg\ kg^{-1}$	Zn $mg\ kg^{-1}$	GY $t\ ha^{-1}$
52	16 x 21	IV	0.22	0.12	0.65	-0.02
53	13 x 21	IV	0.05	0.33	0.37	-0.02
54	14 x 22	IV	0.02	-0.28	-0.03	0.00
55	15 x 22	IV	-0.22	-0.04	-0.03	0.02
56	16 x 22	IV	0.12	0.35	0.21	0.01
57	13 x 23	IV	-0.05	0.37	0.12	0.01
58	14 x 23	IV	0.35	-0.07	0.63	-0.01
59	15 x 23	IV	-0.10	0.22	-0.47	-0.02
60	16 x 23	IV	0.24	-0.27	-1.07*	0.04
61	13 x 24	IV	0.12	-0.41	-1.03*	0.04
62	14 x 24	IV	0.24	0.37	-0.25	-0.02
63	15 x 24	IV	-0.27	-1.00*	0.17	-0.06
64	16 x 24	IV	-0.34	0.50	0.34	0.00
65	5 x 13	V	-0.08	0.20	-0.06	0.02
66	6 x 13	V	-0.02	-0.30	1.01*	0.02
67	7 x 13	V	0.39	0.06	-0.86	0.02
68	8 x 13	V	-0.37	-0.26	-0.44	0.00
69	5 x 14	V	0.48	0.24	-0.51	0.05
70	6 x 14	V	-0.23	-0.20	0.40	-0.02
71	7 x 14	V	-0.16	0.30	1.90	-0.19
72	8 x 14	V	-0.03	-0.55	-0.98	0.02
73	5 x 15	V	0.10	-0.21	1.08*	-0.06
74	6 x 15	V	0.30	0.26	-3.02**	0.00
75	7 x 15	V	-0.18	-0.67	0.31	0.04
76	8 x 15	V	-0.61*	0.02	1.06*	0.02
77	5 x 16	V	-0.82*	-0.20	-0.49	0.03

Table S3 Contd.

S/N	Hybrid	Set	PVA μg g^{-1}	Fe mg kg^{-1}	Zn mg kg^{-1}	GY t ha^{-1}
78	6x 16	V	0.25	0.31	1.29*	-0.06
79	7 x 16	V	-0.10	0.40	0.37	0.00
80	8 x 16	V	0.93*	-0.27	0.22	0.06
81	21 x 17	VI	-0.15	0.27	0.10	-0.02
82	22 x 17	VI	0.09	-0.60	-0.84	0.01
83	23 x 17	VI	0.06	0.89*	-0.01	-0.01
84	24 x 17	VI	-0.03	-0.02	-0.29	-0.02
85	21 x 18	VI	0.24	0.41	-0.31	-0.02
86	22 x 18	VI	0.21	0.54	0.91	0.06
87	23 x 18	VI	-0.64*	-0.32	-0.01	0.01
88	24 x 18	VI	0.12	-0.99*	-1.27*	0.01
89	21 x 19	VI	0.24	0.06	-0.21	-0.01
90	22 x 19	VI	0.21	0.04	-0.46	0.02
91	23 x 19	VI	-0.64	-0.19	-0.11	0.00
92	24 x 19	VI	0.12	0.45	0.68	0.00
93	21 x 20	VI	-0.12	-0.36	0.07	0.00
94	22 x 20	VI	0.21	0.58	0.10	-0.04
95	23 x 20	VI	0.35	-0.21	-1.30*	-0.02
96	24 x 20	VI	-0.28	-0.23	-0.45	-0.02
SE			0.43	0.57	0.78	0.02

PVA: Provitamin A, SE: Standard error.

Table S4. Mean values for agronomic traits of 96 hybrids and 4 checks evaluated across environments

S/N	Hybrid	DA	DS	ASI	PH	EH	PA	EA
1	1 x 9	60.9	62.75	1.84	197.8	103.9	2.45	2.20
2	2 x 9	61.02	62.66	1.64	216.6	110.4	2.42	2.56
3	3 x9	59.82	61.2	1.38	202.1	95.4	2.76	2.71
4	4 x 9	61.68	63.33	1.65	226.5	123	2.5	2.28
5	1 x10	62.32	64.21	1.89	196.8	99.81	2.84	2.9
6	2 x 10	62.77	64.37	1.60	176.2	90.88	3.31	3.36
7	3 x 10	59.4	61.27	1.87	200.8	87.29	3.19	3.08
8	4 x 10	61.74	63.4	1.66	213.2	108.8	2.45	2.12
9	1 x 11	62.2	64.08	1.88	185.2	101.3	3.33	2.80
10	2 x 11	60.37	62.08	1.70	196.5	93.04	2.96	2.38
11	3 x 11	59.39	61.82	2.42	185.2	84.84	3.32	3.30
12	4 x 11	61.67	63.43	1.75	197.2	105.5	2.86	2.20
13	1 x12	61.72	63.51	1.79	199.6	102.6	2.52	2.93
14	2 x 12	62.22	63.7	1.48	225.7	113.4	2.37	2.40
15	3 x 12	59.97	61.39	1.42	205.6	97.42	2.51	2.75
16	4 x 12	61.79	63.53	1.74	229.2	119	2.62	2.76
17	9 x 5	60.43	62.17	1.74	219.4	112.1	2.31	2.32
18	10 x 5	60.94	62.35	1.41	203.9	100.9	2.62	2.62
19	11 x 5	61.22	62.99	1.76	189.3	90.98	2.87	3.13
20	12 x 5	61.09	62.83	1.74	215.3	106.7	2.43	2.49
21	9 x 6	61.79	63.26	1.47	219.2	116.4	2.02	1.99
22	10 x 6	60.93	62.53	1.59	216.7	102.1	2.16	2.14
23	11 x 6	61.42	63.01	1.50	198.1	99.11	2.70	2.39
24	12 x 6	61	62.32	1.31	220.9	111.4	1.92	1.70
25	9 x 7	61.31	62.75	1.43	227.8	124.2	2.38	1.74
26	10 x 7	61.49	62.88	1.38	209.8	106.5	2.56	2.37

27	11 x 7	60.57	62.2	1.63	199.5	106.4	2.68	2.46
28	12 x 7	61.59	63.05	1.46	228.2	123.7	2.32	2.35
29	9 x 8	60.86	62.5	1.63	217.1	114.6	2.16	2.55

Table S4 contd.

S/N	Hybrid	DA	DS	ASI	PH	EH	PA	EA
30	10 x 8	60.63	62.27	1.65	222.00	112.20	2.32	2.54
31	11 x 8	61.66	63.41	1.75	209.00	100.30	2.57	2.20
32	12 x 8	60.83	62.65	1.83	234.40	121.00	2.09	2.16
33	17 x 1	58.92	60.55	1.63	188.80	94.75	2.78	2.90
34	18 x 1	60.70	61.81	1.12	208.00	104.10	2.46	2.72
35	19 x 1	61.98	64.02	2.04	209.00	108.40	2.69	2.76
36	20 x 1	61.03	62.62	1.59	210.30	99.95	2.41	2.63
37	17 x 2	59.40	61.59	2.19	202.40	101.80	2.48	3.14
38	18 x 2	60.62	62.28	1.66	226.10	108.90	2.26	2.54
39	19 x 2	60.51	61.7	1.19	215.60	101.90	2.48	2.36
40	20 x 2	59.79	61.38	1.59	221.60	107.40	2.88	2.76
41	17 x 3	60.66	62.5	1.84	200.30	90.52	2.58	2.19
42	18 x 3	58.60	60.12	1.51	223.80	96.58	2.76	2.82
43	19 x 3	57.62	59.83	2.20	214.00	96.06	2.92	3.04
44	20 x 3	60.36	61.98	1.62	189.90	83.80	3.21	3.26
45	17 x 4	59.31	61.02	1.70	203.20	99.66	2.44	2.58
46	18 x 4	58.63	60.27	1.64	224.90	113.70	2.28	2.13
47	19 x 4	60.63	62.24	1.61	225.40	113.40	2.53	2.44
48	20 x 4	59.39	61.02	1.62	206.70	98.67	2.83	2.48
49	13 x 21	59.24	61.13	1.88	196.10	99.95	2.51	2.67
50	14 x 21	57.13	58.66	1.52	191.80	96.32	2.80	2.49
51	15 x 21	59.30	61.05	1.74	189.40	91.13	2.71	2.49
52	16 x 21	59.53	61.17	1.64	195.30	102.30	2.31	2.44
53	13 x 22	60.39	62.09	1.69	220.20	101.80	2.66	2.49
54	14 x 22	59.90	61.61	1.71	210.20	94.74	2.31	2.40
55	15 x 22	60.97	62.7	1.72	201.70	86.71	2.62	2.35

56	16 x 22	61.27	63.17	1.89	207.00	95.64	2.32	2.02
57	13 x 23	60.86	62.43	1.57	204.40	102.20	2.31	2.49
58	14 x 23	61.27	62.95	1.68	202.80	107.50	2.51	2.03
59	15 x 23	62.43	64.22	1.78	193.50	87.64	3.05	2.57
60	16 x 23	62.79	64.64	1.84	196.70	102.10	1.94	1.69

Table S4 contd.

S/N	Hybrid	DA	DS	ASI	PH	EH	PA	EA
61	13 x 24	58.19	59.76	1.57	202.40	94.40	2.76	2.75
62	14 x 24	57.86	59.35	1.49	199.00	97.80	2.79	2.72
63	15 x 24	59.21	60.66	1.45	187.30	82.28	3.16	2.86
64	16 x 24	60.03	61.75	1.72	194.40	94.30	2.72	2.54
65	5 x 13	59.46	61.30	1.84	226.80	103.60	2.04	2.54
66	6 x 13	60.25	61.97	1.72	218.80	110.10	1.90	2.01
67	7 x 13	59.93	61.71	1.78	238.20	124.90	2.38	2.30
68	8 x 13	60.52	62.53	2.01	233.00	122.20	2.38	2.76
69	5 x 14	60.26	61.89	1.63	200.30	104.60	2.68	2.40
70	6 x 14	61.67	62.59	0.92	202.40	101.20	2.73	2.24
71	7 x14	64.28	65.51	1.23	178.30	92.86	3.51	3.71
72	8 x 14	61.17	62.82	1.65	217.70	108.40	2.43	2.61
73	5 x 15	61.74	63.38	1.64	205.20	87.44	2.99	2.65
74	6 x 15	57.31	58.67	1.36	194.80	87.82	2.76	3.06
75	7 x 15	61.18	62.95	1.76	215.30	97.24	2.13	2.63
76	8 x 15	60.83	62.64	1.81	219.10	101.50	2.13	2.35
77	5 x 16	61.84	63.35	1.51	209.80	104.70	2.44	2.40
78	6 x 16	63.00	64.66	1.66	203.00	102.70	2.35	2.26
79	7 x 16	61.95	63.60	1.66	214.80	119.50	2.47	2.32
80	8 x 16	61.47	63.09	1.62	211.70	110.60	2.19	1.96
81	21 x 17	56.58	57.88	1.30	180.70	86.46	2.90	2.66
82	22 x 17	56.99	58.40	1.41	189.30	84.46	2.69	2.56
83	23 x 17	60.39	62.22	1.82	188.00	92.12	2.57	2.50
84	24 x 17	56.80	58.26	1.46	185.40	83.88	3.06	2.98

85	21 x 18	58.80	60.26	1.46	199.10	98.10	2.64	2.84
86	22 x 18	58.06	59.26	1.20	216.90	98.22	2.37	2.16
87	23 x 18	60.72	62.34	1.63	218.40	106.30	2.70	1.86
88	24 x 18	56.38	57.74	1.37	195.70	88.51	3.15	2.37
89	21 x 19	57.36	58.98	1.62	192.70	91.12	2.77	2.63

Table S4 contd.

S/N	Hybrids	DA	DS	ASI	PH	EH	PA	EA
90	22 x 19	59.12	60.30	1.18	199.70	91.54	2.87	2.71
91	23 x 19	60.82	62.67	1.85	192.30	96.44	3.10	2.43
92	24 x 19	57.06	58.67	1.61	198.40	95.12	2.99	2.65
93	21 x 20	56.03	57.64	1.61	180.40	88.63	3.06	2.87
94	22 x 20	59.20	60.58	1.38	193.40	83.25	3.01	2.68
95	23 x 20	61.89	63.26	1.37	185.80	92.18	3.03	2.64
96	24 x 20	57.18	58.50	1.32	192.80	88.09	3.17	2.91
Ife Hybrid-3	Check	58.90	60.43	1.53	188.90	91.91	2.34	2.25
Ife Hybrid-4	Check	62.13	64.16	2.04	223.00	114.40	2.40	1.80
M1124-31	Check	59.34	61.06	1.73	202.20	100.40	2.41	2.05
Oba Super 2	Check	60.40	62.02	1.63	192.10	95.20	2.96	2.89
Grand mean		60.26	61.8	1.63	205.51	100.87	2.61	2.52
LSD($p<0.05$)		0.67	0.67	0.33	10.03	6.93	0.17	0.16

DA: no. of days to anthesis, DS: no. of days to silking ASI : anthesis silking interval (days to 50% silking minus days to 50% male flowering), EH : Ear height, PH : plant height, PA : plant aspect and EA : ear aspect, LSD: Least Significant difference.

Table S5: The Physical and chemical properties of soils (0-30cm) of the study sites

Soil properties	2020		2021		Critical level (Chude et al., 2012
	Ikenne	Saminaka	Ikenne	Saminaka	
pH (1:1, H_2O)	4.7	5.0	4.7	5.6	Neutral 6.6-7.2
Organic carbon ($mgkg^{-1}$)	9.5	7.4	9.6	7.9	10-14
Total Nitrogen (gkg^{-1})	1.1	1.2	0.9	1.0	
Available P ($mgkg^{-1}$)	28.7	72.2	23.5	65.6	16-2.0
Exchangeable acidity	0.9	0.9	1.0	0.9	
Exchangeable cations ($cmol\ kg^{-1}$)					
K	1.1	0.5	1.0	0.3	
Mg	1.2	0.3	1.2	0.4	0.3-0.6
Ca	2.3	0.3	2.6	0.3	
Na	0.5	0.2	0.7	0.2	
Extractable micronutrients ($mgkg^{-1}$)					
Fe	18.5	170.4	30.5	140.3	
Mn	53.4	18.0	58.7	20.5	
Cu	3.0	1.6	2.8	1.4	
Zn	2.5	8.0	2.1	7.0	
Particle Size distribution (gkg^{-1})					
Sand	820.0	720	812.0	740.0	
Silt	80.0	200	88.0	192.0	
Clay	100.0	80	102.0	68.0	
Textural class (USDA)	Loamy sand	Sandy loam	Loamy sand	Sandy loam	

Table S6: Agroecological zones, average rainfall, temperature, relative humidity and soil type of the study locations

Locations	Agroecology	Average rainfall/month (mm)		Average temperature /month (°C)		Average Relative Humidity (%)		Soil Type (FAO Classification)
		2020	2021	2020	2021	2020	2021	
Ikenne	Rainforest	103.6	106.6	28.0	27.9	87.0	87.8	Luvisols, Acrisols, Ferrasols and Lithosols
Saminaka	Southern guinea savanna	79.5	62.2	25.0	24.9	63.0	61.4	Luvisols

Source: IITA Geographic Information System