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COMBINING ABILITY FOR GRAIN YIELD AND NUTRITIONAL QUALITY OF MAIZE GROWN IN MALAYSIA: A REVIEW

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SUMMARY

Maize breeding appears to be a key strategy to ensure global food security. Improving the grain yield and nutritional quality of maize can progress through breeding programs, where hybridization between two genetically contrasting inbreds might lead to producing superior hybrids. This phenomenon occurs as the developed hybrids are 100% heterozygous, and in consequence, expressing heterosis. However, to select parents for the ideal combinations, it is fundamental to understand the genetic status and the ability to combine the different inbreds. This review aimed to highlight the effectiveness of the general combining ability (GCA) and the specific combining ability (SCA) approaches to develop high-yielding and nutritionally enriched maize hybrids adapted to Malaysia´s conditions. Maize breeders have applied various breeding methods, including the biofortification technique to augment the grain yield and nutritional quality of the crop. This technique is the most sustainable, feasible, and affordable one, as it offers more nutritious plants with the required micronutrients. Although a considerable amount of research has succeeded in identifying potential inbred combinations for specific traits and sites, the application of combining ability methods toward developing high-yielding and nutritionally enriched maize hybrids adapted to Malaysia´s conditions has not been maximized. Therefore, it is important to understand the combining ability approaches to develop maize hybrids that could lead to the maximum output for combating the increasing maize global demand.

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Keywords: Combining ability, grain yield, nutritional quality, maize breeding, biofortification

Key findings: This review points out the significance of the general and specific combining ability approaches to develop high-yielding and nutritionally enriched maize hybrids.

INTRODUCTION

Fundamentally, the people in the world get the necessary food for living. However, this objective is often unachievable due to various factors, such as the Covid-19 pandemic in 2020, where many people suffering from food insecurity increased by 21% (160 million people) compared with the previous year (Baquedano *et al.,* 2021). Moreover, maize might represent a positive solution to this food insecurity problem, as many countries in Latin America, Africa, and Asia consider it as a staple food and a high-priority crop. Maize is the third most valuable cereal after wheat and rice, although, compared with those two crops, maize can serve many more purposes (Erenstein, 2010). In Malaysia, maize has become the principal component of animal feeds, however, 100% remains an import. Nonetheless, locally developing maize seeds through plant breeding can reduce a significant part of the import bills and, more importantly, ensure self-sufficiency (UN Comtrade, 2019).

Plant breeding could be a prime approach to overcome these food problems, relevant to farmers and consumers (Lenaerts *et al*., 2019). It can favor plant characteristics, such as higher adaptability to extreme conditions, increased productivity, and better nutritional quality. In that sense, breeding maize to develop new varieties and hybrids with better characteristics might represent a wise strategy to augment food security, as maize is grown worldwide on around 160 million hectares of land (Silva *et al.,* 2017).

Maize breeding efforts often seek productivity and for the association between traits and variables related to yield. Notwithstanding, in addition to that, nutritional quality is also a desired feature that aims to improve the food security of the nations, especially of developing ones. However, it is crucial to understand that due to the complexity of both traits´ expression (the kernel yield and the nutritional content), it is hard to select adequate inbred combinations that will form the best hybrids in terms of nutritional quality and grain yield (Sprague and Tatum, 1942).

In that way, the combining ability approach appears as a fundamental method to determine the best possible combiners that can generate outstanding hybrids for the desired characteristics. Among the various plant breeding techniques, combining ability analysis is a forceful method to determine the fitness of inbred lines in crosses, either to exploit the heterosis or to amass suitable genes. In other words, it is central to identify inbred lines with the highest ability to combine to develop hybrids with desirable genes or characters (Sprague and Tatum, 1942).

This review addresses in detail the methodology used of the combining ability approach and its effectiveness in developing high-yielding and nutritionally enriched maize hybrids, benefiting as a guide to facilitate the selection of parents and breeding strategies for maize hybrid development in Malaysia.

Food security

Food security has been a valid chief concern at all levels. In 2019, an estimation stated that 8.9% of the world population was undernourished, even though food production remained constant (FAO *et al.,* 2021). Correspondingly, eliminating hunger does not just correlate to the amount of food produced, as it also depends on guaranteeing all people adequate access to safe and nutritious food in the necessary quantities as one of the main goals of the planet (UN, 2017).

Moreover, governments are fully responsible of supporting citizens to get food for a good living (FAO *et al*., 2021). The Malaysian economy, for instance, has been showing an average growth of 5.4% between 2010 and 2018. However, its food security status is not at its healthiest, as the import bill is causing a deficit, and more food needs local production to ensure self-sufficiency (Fakhrul and Chua, 2021; Wan-Manan *et al*., 2019).

Maize breeding

Maize (*Zea mays* L.), an annual cereal crop grown all over the globe, belongs to the Gramineae family. Many countries in Latin America, Africa, and Asia consider maize a staple food and is the third most valuable cereal after wheat and rice. Nonetheless, compared with those two crops, maize has many more purposes. In developed countries, it mainly serves as livestock feed, although it can also be processed. In addition, each year, the demand for maize increases as animal feed consumption requires rapid augmentation due to global economic growth (Erenstein, 2010).

In Malaysia, maize has become a high-priority source to produce wealth for the country, as it is a fundamental component in animal feed formulation. However, for more than 50 years, the nation has been relying 100% on imported seeds, which translates into around RM 3 billion (USD 645 million) (UN Comtrade, 2019). From 2016 to 2017, Malaysia imported 3.5 tons due to the approval of USA maize among the feed millers of the country, as the maize grain industry in Malaysia is relatively small, even though its livestock industry requires millions of tons of maize for their feeds (Wahab, 2017).

Notwithstanding, as time passes, the maize grain production in the country is also slowly decreasing, as it is being replaced by sweet corn since its production cost is inferior and has a faster phenological period. From 2003 to 2015, the sweet corn cultivation area increased by 77%, and its production increased by 62%. Consequently, those 15 years neglected maize cultivation, making the country dependent on corn imports (Nor *et al.,* 2019).

In addition to these circumstances, other external factors need consideration to attain the demand for the quality and quantity standards required. One of these factors has undoubtfully been the Covid-19 pandemic, which staggered the whole worldwide food supply chain (from the field to the final consumer) by restricting the movement of workers, changing the demand, closing food production facilities, limiting food trade policies and increasing financial pressures in the entire food supply chain (Aday and Aday, 2020).

Numerous solutions have emerged to overcome these challenges, such as higher automation in food production and processing systems, increasing the emphasis on protected cropping (Henry, 2019), and speeding up the placement and distribution of improved crop varieties (Pouvreau *et al*., 2018) to the most affected areas. For that reason, maize breeding appears crucial to the downfall of the pandemic’s adverse effects and other causes by adapting to this situation and rapidly delivering newly developed cultivars to these limited locations (Henry, 2020).

Moreover, the constant evolution in plant breeding has always been progressing, as each time, new techniques and understandings appear to develop more efficiently new materials despite the vagaries of climate and disease attacks (Muntean *et al*., 2022). Since 2011, genome editing (GE) technology has become a dominant tool in plant breeding, as it focuses on precisely modifying the crop genome at specific sites to enhance the beneficial characteristics of plants and remove the negative ones without adding anything else that was not already there (Nerkar *et al*., 2022).

In addition, it is essential to realize that even though new technologies in plant breeding have emerged, it is still crucial to keep having conventional breeding programs. Combining traditional breeding programs with other branches of science will more successfully contribute to gaining better results. In that way, independently of the technologies a breeding program relies on, it is fundamental to have conventional maize breeding programs with the basic structure to place the genetic materials in evaluating trials or in experimental nurseries (Figure 1). In the evaluation trials, potential hybrids’ establishment will identify the best ones compared with the most competitive commercial hybrids already available in the market. However, in the experimental

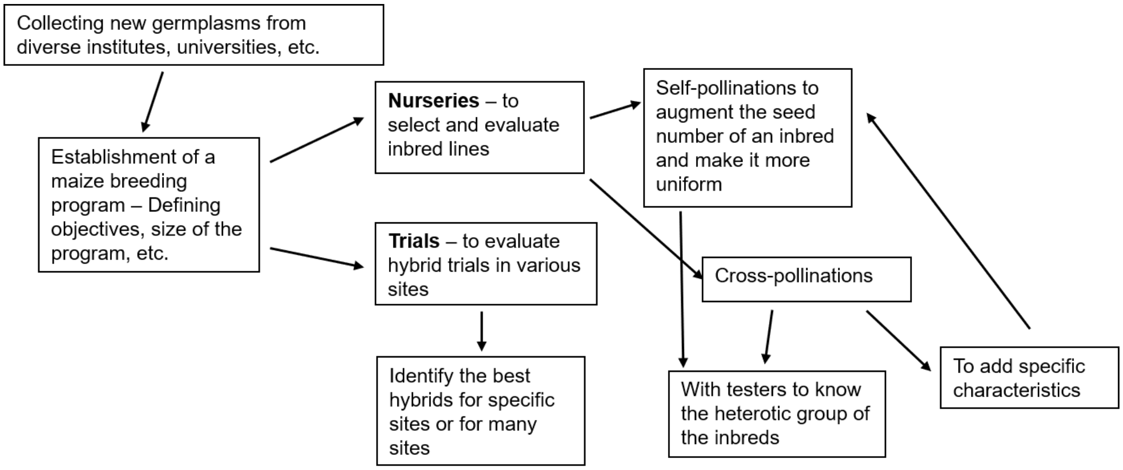

Figure 1. Maize breeding process suggested by Lenaerts *et al*. (2019).

nurseries, inbreds' advancement will augment their homozygosity level to increase their seed number or even to cross them with other sources to develop a hybrid with better characteristics (Lenaerts *et al*., 2019).

A better example of these results is the climate-resilient maize varieties CIMMYT and several national programs in eastern and southern Africa have developed. These varieties yielded between 20%–25% more than commercial varieties in on-farm trials under low-input and drought-stress conditions (Setimela *et al*., 2017). However, the yields of the succeeding developed varieties only have an expected growth of 3 mg ha^{-1} in 17 years under random stress conditions. Nonetheless, if increasing genetic gains, then a rise in yields could also appear (Li *et al.,* 2018). Similarly, to increase genetic gains through maize breeding, integrating modern tools and strategies, such as high-density genotyping, double haploid technology, molecular marker-assisted selection, and genomic selection-based breeding is necessary (Cairns and Prasanna, 2018).

Maize breeding in Malaysia has been in the government's sights for several years. In 2016, the Malaysian Ministry created a Grain Corn Development Master Plan from 2018 to 2032 where the aim is to allow the country to produce 30% of the grain corn required for domestic consumption (around 1.4 million tons of grain to fill the requirements until 2032) (Nor *et al*., 2019). Since then, every player in the whole food supply chain has been considered, including the maize breeders responsible for creating local maize hybrids and varieties to reduce reliance on imports (Nor *et al.,* 2019).

The Malaysian Agricultural Research and Development Institute (MARDI) and the private company Green World Genetics (GWG) have been playing a crucial function in implementing the research in maize, mainly focusing on creating high-yielding hybrids based on suitability to the land and conditions in Malaysia (Nor *et al.,* 2019). Table 1 shows some of the locally developed Malaysian maize hybrids tested in Terengganu, where the hybrid GWG 333 obtained the highest yield with 8.9 t/ha. Moreover, Saleh *et al.* (2002) selected 12 maize inbred lines acquired from the Philippines, Thailand, and Indonesia to develop new hybrids using a diallel crossing scheme. From their study, the hybrid UPM-MT-5 × UPMSM5-4 (Hy-60) showed as the best one with 5.94 t/ha, was just a few kilograms below Putra J-58, the local hybrid check, which the Universiti Putra Malaysia developed, giving a yield of 6.2 t/ha (Table 2).

The presence of pests and diseases in maize under BRIS (Beach Ridges Interspersed with Swales) soils also incurred evaluation (Sulong *et al.,* 2019), as this soil type occurs

Table 1. Yield of local hybrids tested in Terengganu, Malaysia in 2016 (Nor *et al.,* 2019).

Hybrid	Developed by	Yield (t/ha)
GWG 333	Green World Genetics, Malaysia	8.9
GWG 555	Green World Genetics, Malaysia	5.1
GWG 888	Green World Genetics, Malaysia	9.3
GWG 111	Green World Genetics, Malaysia	7.6

Table 2. Top-yielding maize hybrids developed from the diallel crosses in Malaysia (Saleh *et al*., 2002).

Hybrid	Developed by	Yield (t/ha)
UPM-SM5-9 X UPMTW-5 (Hy-17)	Universiti Putra Malaysia	5.01
UPM-SM5-5 X UPMTW-12 (Hy-18)	Universiti Putra Malaysia	5.18
UPM-SW5-4 X UPMTW-12 (Hy-19)	Universiti Putra Malaysia	5.09
UPM-SW-2 X UPMTW-5 (Hy-33)	Universiti Putra Malaysia	4.96
UPM-SW-9 X UPMSM5-9 (Hy-43)	Universiti Putra Malaysia	5.29
UPM-MT-5 X UPMSM5-9 (Hy-45)	Universiti Putra Malaysia	5.51
UPM-MT-5 X UPMSM5-5 (Hy-53)	Universiti Putra Malaysia	5.25
UPM-SW-9 X UPMSM5-4 (Hy-58)	Universiti Putra Malaysia	5.65
UPM-MT-13 X UPMSM5-4 (Hy-59)	Universiti Putra Malaysia	5.72
UPM-MT-5 X UPMSM5-4 (Hy-60)	Universiti Putra Malaysia	5.94
Hybrid Checks:		
Swan 1	Farm Swan, Thailand	5.43
Swan 3	Farm Swan, Thailand	4.47
Metro	Metroseed, Indonesia	5.1
Putra J-58	Universiti Putra Malaysia	6.2

extensively along the east coast of peninsular Malaysia (160,090 ha). Nonetheless, many research areas still need consideration, such as developing heat-tolerant maize hybrids and varieties, as Malaysia has a tropical climate with an average annual temperature of 27.6 °C (Phung *et al*., 2023). Kandel *et al*. (2019) in Nepal conducted research on this matter, and based on the combination of the stress susceptibility index (SSI), the stress tolerance index (STI), the tolerance index (TOL), the geometric mean productivity (GMP), and the mean productivity (MP) helped the selection to identify superior heat stress tolerant lines.

It is necessary for an active contribution of all parties involved in the food supply chain to achieve Malaysia's Grain Corn Development Master Plan goal, not only relying on maize breeding. The united efforts of all parties could then bring significant results, and even better if all these ideas are followed through by developing a research network at the Association of Southeast Asian Nations (ASEAN) level (Nor *et al*., 2019).

Maize nutritional composition

The percentages of the maize nutritional composition might change according to the different corn varieties' genetic background, plant age, and distinct environmental and topographical conditions where they were grown (Nazli *et al*., 2019), and even during kernel processing. Moreover, independent of the nutritional variation due to the mentioned factors, maize contains other indispensable elements such as copper, iron, nickel, manganese, zinc, carotenoids, and phytosterols (Demeke, 2018).

Table 3 displays the nutritional content of four grown maize varieties (including sweet corn) in Malaysia at distinct harvesting stages. A significant difference between stages per variety occurred for crude protein (CP), neutral detergent fiber (NDF), hemicellulose, and acid detergent fiber (ADF). In addition, there was also a significant difference in CP and lignin among the distinct varieties. Similarly, remarkable differences between the harvesting

Table 3. Nutritive values of the different corn varieties at different harvest stages grown in Malaysia (Nazli *et al.,* 2019).

Items	CP	NDF	Hemi-cellulose	ADF	Lignin
ANOVA					
Harvest stage (H)	*	**	**	**	Ns
Variety (V)	**	ns	Ns	ns	**
H x V	ns	ns	**	**	Ns
Sweet corn					
Silking	11.7a	66.2a	22.1c	44.1a	5.92ª
Milk	11.7a	60b	24.5c	35.4b	6.35ª
Dough	10.7a	62.9ab	32.2b	30.8bc	6.02ª
Dent	11.7a	65.2a	38.7ª	26.5c	5.49ª
Means	11.4a	63.6a	29.4ª	34.2a	5.95a
Suwan					
Silking	11.8a	65.2a	21.8b	43.4a	7.08ª
Milk	11.2ab	63.8a	31ª	32.8b	7.45ª
Dough	10.7b	64.5a	30.4ª	34.1b	7.44ª
Dent	9.6c	63.5a	32.2ª	31.3b	7.66ª
Means	10.8ab	64.2a	28.8ab	35.4a	7.41a
BTL2					
Silking	11.2ab	64.6a	27.4ª	37.2a	5.44ª
Milk	10.7a	61.1b	24.9ª	36.2a	6.72ª
Dough	8.7a	62.3ab	27.4ª	34.9a	6.91ª
Dent	9.8a	64ab	26.5ª	37.5a	7.16ª
Means	10.1B	63a	26.5b	36.5a	6.55bc
BTL1					
Silking	11.1a	63.8a	20.6b	43.3a	6.6ª
Milk	10.3a	65.3a	28.3ª	37.1b	6.97ª
Dough	9.89a	63.2a	29.4ª	33.8bc	7.03ª
Dent	9.69a	63.9a	33.4ª	30.6c	7.14ª
Means	10.2B	64.1a	27.9ab	36.2a	6.93ab

BTL- breeding test line, ANOVA-analysis of variance, ns-no significant difference, CP-crude protein, NDF-neutral detergent fiber, ADF-acid detergent fiber. All the means are presented in percentages. * Significant at $P < 0.05$, ** significant at $P < 0.01$. Harvest stage means within each variety having similar small letters are not significantly different, variety means with similar capital letters are not significantly different.

stages × variety interactions were evident in the ADF and hemicellulose. Based on these results, sweet corn showed higher CP and lower lignin contents than the three maize varieties used in the study (Nazli *et al*., 2019).

On the other hand, maize has similar amounts of protein, carbohydrates, fat, and fiber compared with soybean, sorghum, rice, and wheat (Figure 2A). It has a comparable amount of calcium, iron, magnesium, phosphorus, potassium, sodium, zinc, copper, and manganese to rice, sweet potato, and yam (Figure 2B). However, maize is deficient in vitamin C, and sorghum lacks vitamins C, B6, A, and E, while potato and cassava are the crops with higher amounts of these vitamins (Figure 2C). Maize has a similar proportion of vitamins A and E compared to rice and yam, although the crops with higher amounts of these vitamins are soybean and sweet potato (Galani *et al.,* 2022).

Interestingly enough, Bojtor *et al.* (2022) evaluated the effect of nitrogen fertilizer on maize nutrition and found that applying 120 kg ha^{-1} of it increases the amount of crude protein, then translates into an improved maize quality for forage. Moreover, they detected that augmenting the fertilizer dosage increases the potassium content in stems and leaves, the calcium content in stems, the sulfur content in all tissues, the iron content in leaves and seeds, the copper content in leaves, stems, and cob, and the manganese content in leaves, seeds, and cob.

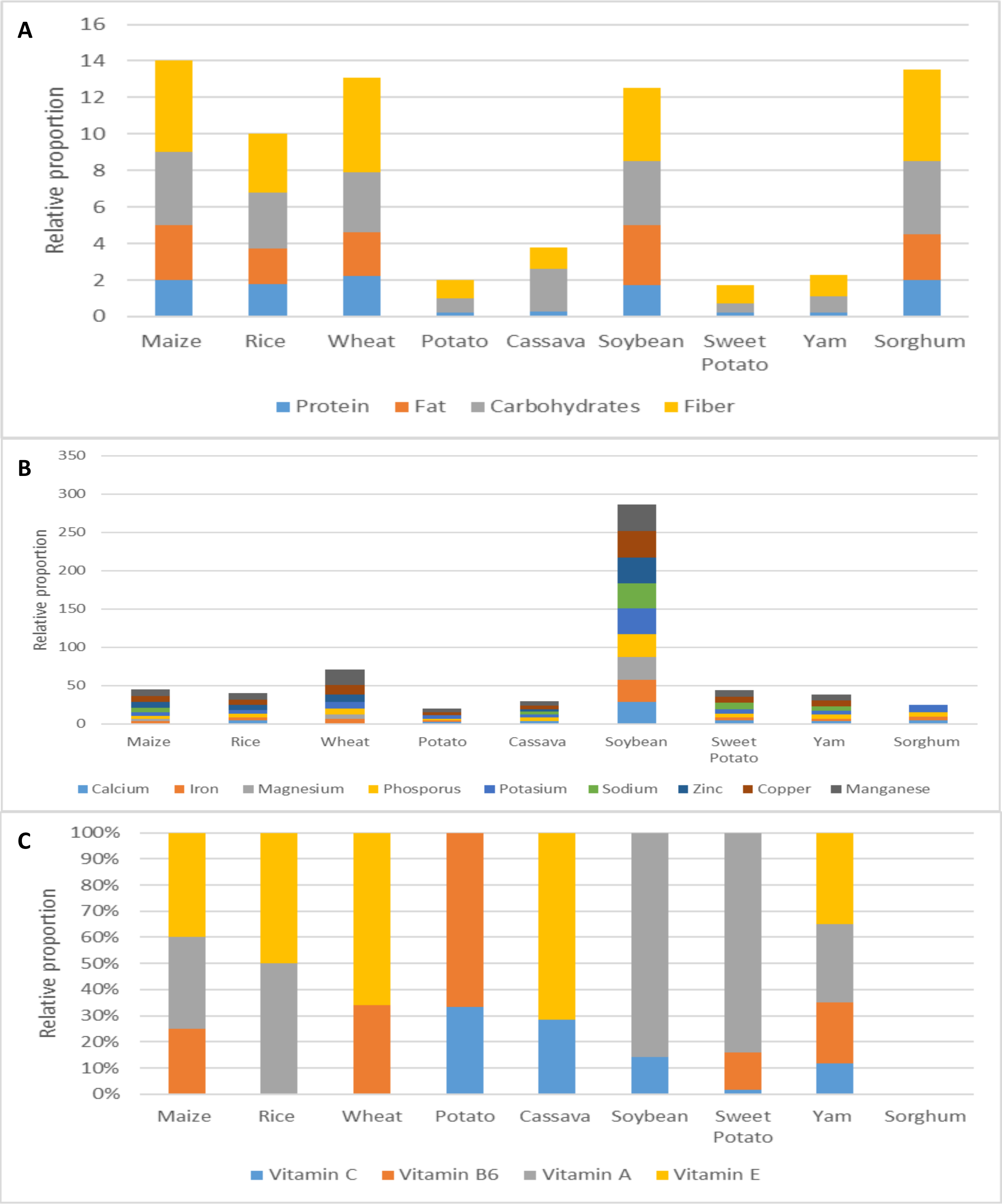

Figure 2. Comparison of nutrients per 100 g portion between maize and other crops (Galani *et al.*, 2022). A) Protein, fat, carbohydrates and fiber, B) Calcium, iron, magnesium, phosphorus, potassium, sodium, zinc, copper and manganese, C) Vitamin C, vitamin B6, vitamin A, and vitamin E.

Furthermore, they also discovered that this fertilizer boosted the magnesium content in leaves, stems, and cob, the zinc content in all tissues, the molybdenum content in leaves, and the nickel content in the grain. The report revealed leaves were the plant tissues with the highest susceptibility to the amount of fertilizer used, while the cob and the seeds had the lowest variation (Bojtor *et al.,* 2022).

Combining ability

Combining ability is the breeding aptitude of parental lines to produce hybrids. Sprague and Tatum (1942) established the concept for use in breeding programs to produce superior hybrids. The general combining ability effect has influences from the additive gene action, then used to detect the general hybrid performance of a parental inbred crossed with different genotypes. A high general combining ability (GCA) denotes a massive involvement of additive gene effects. Moreover, the specific combining ability (SCA) gains effects from the dominant gene action, applicable to indicate the hybrid performance in specific combinations. Notwithstanding, both variance components are beneficial in identifying the gene action and evaluating the genetic potential of the parents in hybrid pairings.

Performing the combining ability analysis can use the following model of Gardner and Eberhart (1966):

$$X_{ij} = \mu + g_i + g_j + S_{ij} + e_{ij}$$

Where:
X_{ij} = the value of the progeny derived from the crossing of the ith female parent with the jth male parent;
μ = the mean effect for all progenies;
g_i = the GCA effects of the ith female parent;
g_j = the GCA effects of the jth male parent;
S_{ij} = the SCA effects specific to the hybrid of the ith female and the jth male lines; and
e_{ij} = the experimental error (between ith and jth lines).

The relative importance of the general and specific combining abilities on the progeny performance is obtainable with the following ratio (Baker, 1978):

$$\text{GCA and SCA ratio} = \frac{2MS_{GCA}}{(2MS_{GCA} \pm MS_{SCA})}$$

Where:
MS_{GCA} = the mean square of GCA and
MS_{SCA} = the mean square of SCA.

Correspondingly, breeders could benefit from the combining ability results, as the promising genotypes with the highest capacity to combine reach selection to increase the chances of developing outstanding hybrids. Likewise, it is also vital to determine the heritability and genetic variability of the population, as with that knowledge, there would be higher chances of augmenting the program's effectiveness with significant results (Begna, 2021). In that way, if the general and specific combining abilities are not substantial, the epistatic effects might affect the distinct genetic traits (Sprague and Tatum, 1942).

The combining ability approach might be fundamental to strengthening the food security of the nations (Kumar *et al*., 2015; Nadeem *et al*., 2023; Tabu *et al*., 2023). It helps to develop more productive crops adapted to all types of stresses and conditions. Figure 3 shows that identifying specific varieties combining successfully to produce outstanding hybrids based on their agronomic and nutritional performance can result in more yields and profits for the farmers. Likewise, the consumers will benefit as they get more nutritious food, contributing to a robust food security status (Begna, 2021).

In this matter, Wahab (1997) experimented to determine the combining ability of six maize varieties in Malaysia. The variety Nakhorn Suwan 1 was the one with the best general combining ability for yield, plant height, ear height, and husk cover, and the ear aspect was the only trait where this variety showed negative numbers, indicating a negative heterosis for this specific characteristic (Table 4). Negative heterosis for plant height, maturity time, and other traits

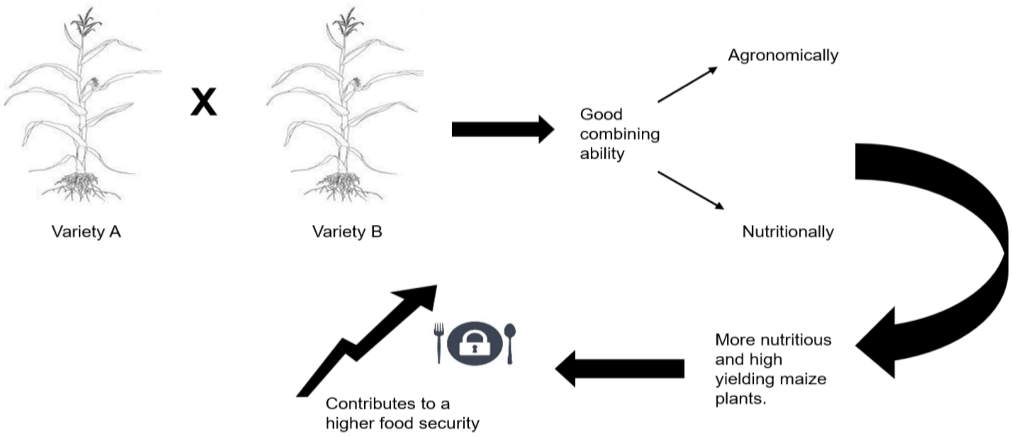

Figure 3. Contribution of good combining ability in maize breeding to increase food security (Begna, 2021).

Table 4. Estimates of GCA effects for yield, 50% tasseling, plant and ear heights, husk cover, and ear aspect for six varietal parents (Wahab, 1997).

Variety	Developed by	Yield	50% tasseling (days)	Plant height (cm)	Ear height	Husk cover	Ear aspect
Bertam 8805	MARDI, Malaysia	274.42	-0.53	-2.52	-3.31	-0.04	-0.17
Bertam 8602	MARDI, Malaysia	-128.71	-0.4	-7.37	-3.79	-0.08	0.04
Bertam 8701	MARDI, Malaysia	-385.83	0.76	-0.75	0.66	0	0.04
Pop. 28	MARDI, Malaysia	-79.67	0.01	-1.72	-1.25	-0.08	0.04
Suwan 3	Farm Swan, Thailand	-226.92	0.1	3.22	3.12	0.08	0.08
Nakhorn Suwan 1	Farm Swan, Thailand	546.71	0.06	9.14	4.58	0.13	-0.04
SE (gi)*		241.52	0.19	3.12	1.99	0.12	0.14
SE of diff. (gi - gj)		374.16	0.3	4.83	3.08	0.18	0.21

*gi is the estimated average performance of a parent line i crossed with each of the other parent lines, compared with the overall mean performance of the P parents and 1 set of F1s.

could be beneficial in many situations as it demonstrates the superiority of the hybrids over the parents. Hence, parental varieties could gain selection if these have positive values of heterosis for yield and either positive or negative for plant/ear height and maturity time. For that reason, the variety Bertam 8805 could also be a better parental choice to form a composite variety, a new hybrid, or as a germplasm source of a maize improvement program.

The best combinations for yield were Bertam 8701 × Suwan 3, Bertam 8602 × Pop. 28, and Bertam 8701 × Nakhorn (Table 5). Interestingly, it was notable that some parental varieties presenting a better general combining ability did not show positive effects when crossing them. It happened to Bertam 8805 and Nakhorn Suwan 1, as shown in Table 5. Both demonstrated themselves to be good combiners, but when they underwent crossing, the resulting hybrid displayed negative values. Moreover, as just a few of the crosses used for this study had a low magnitude of heterosis and none beat Nakhorn Suwan 1 in yield, developing a hybrid from these specific crosses is not viable. In that sense, another alternative to use these varieties is to produce two breeding populations providing significant heterosis when crossed and acceptable genetic variation to allow a fast advancement from recurrent selection (Eberhart *et al.*, 1967).

Table 5. Estimates of SCA effects for yield, 50% tasseling, plant and ear heights, husk cover, and ear aspect for 15 varietal crosses and their self-pollination (Wahab, 1997).

Cross	Developed by	Yield	50% tasseling (days)	Plant height (cm)	Ear height (cm)	Husk cover	Ear aspect
Bertam 8805 x Bertam 8805	MARDI, Malaysia	-432.55	1.98	-11.42	-7.04	-0.39	0.48
Bertam 8805 x Bertam 8602	MARDI, Malaysia	-103.76	0.8	4.75	3.23	0.98	0.27
Bertam 8805 x Bertam 8701	MARDI, Malaysia	52.7	-2.03	12.1	9.41	-0.43	-0.4
Bertam 9905 x Pop. 28	MARDI, Malaysia	651.87	-0.95	2.17	-0.18	-0.35	-0.4
Bertam 8805 x Suwan 3	MARDI, Malaysia	758.12	-2.03	10.34	8.39	0.48	-0.11
Bertam 8805 x Nakhorn Suwan 1	MARDI, Malaysia	-493.84	0.35	-6.52	-6.77	0.11	-0.32
Bertam 8602 x Bertam 8602	MARDI, Malaysia	516.04	0.01	12.89	5.68	0.02	-0.61
Bertam 8602 x Bertam 8701	MARDI, Malaysia	-2515.51	1.51	-21.36	-14.68	0.94	2.06
Bertam 8602 x Pop. 28	MARDI, Malaysia	1024.66	-1.07	-2.49	2.2	-0.31	-0.27
Bertam 8602 x Suwan 3	MARDI, Malaysia	233.58	-0.82	-7.99	-11.34	-1.14	-0.32
Bertam 8602 x Nakhorn Suwan 1	MARDI, Malaysia	328.95	-0.45	1.29	9.24	-0.52	-0.52
Bertam 8701 x Bertam 8701	MARDI, Malaysia	447.29	1.68	0.56	4.93	-0.14	-0.61
Bertam 8701 x Pop. 28	MARDI, Malaysia	-1271.21	0.1	-7.84	-6.89	0.94	0.73
Bertam 8701 x Suwan 3	MARDI, Malaysia	1906.37	-1.32	-1.54	1.44	-0.89	-0.65
Bertam 8701 x Nakhorn Suwan 1	MARDI, Malaysia	933.08	-1.61	17.51	0.85	-0.27	-0.52
Pop. 28 x Pop. 28	MARDI, Malaysia	1098.62	0.51	12.6	7.65	-0.31	-0.94
Pop. 28 x Suwan 3	MARDI, Malaysia	-1867.13	0.43	-14.9	-6.95	0.19	1.02
Pop. 28 x Nakhorn Suwan 1	MARDI, Malaysia	-735.42	0.47	-2.16	-3.48	0.15	0.81
Suwan 3 x Suwan 3	MARDI, Malaysia	459.12	1.35	14.33	8.28	0.36	-0.69
Suwan 3 x Nakhorn Suwan 1	MARDI, Malaysia	-1949.17	1.05	-14.56	-8.11	0.65	1.43
Nakhorn Suwan 1 x Nakhorn Suwan 1	MARDI, Malaysia	958.28	0.1	2.22	4.13	-0.06	-0.44
SE of diff. (Sii - Sjj)		748.32	0.6	9.65	6.15	0.37	0.43
SE of diff. (Sij - Sik)		989.94	0.8	12.77	8.14	0.49	0.57
SE of diff. (Sij - Skl)		916.5	0.74	11.82	7.53	0.45	0.52

*Sij is the estimated 'extra' performance when line i is crossed with line j, in addition to that measured by gi and gj, compared with the overall mean.

Table 6. List of some of the provitamin A, zinc, and quality protein biofortified maize varieties released in different countries across the world (Goredema-Matongera *et al.,* 2021).

Variety	Target Trait	Target Countries	Year of Release
BIO-MZN01	Zinc	Colombia	2018
ICTA HB-15	Zinc	Guatemala	2018
ICTA B-15	Zinc	Guatemala	2018
GV665A	Provitamin A	Zambia	2012
GV662A	Provitamin A	Zambia	2012
Abontem	Provitamin A	Ghana	2012
MH39A, MH40A	Provitamin A	Malawi	2016
ZS242A	Provitamin A	Zimbabwe	2015
RAHA02	Provitamin A	Rwanda	2017
HQPM-5	QPM	India	2007
Obatanpa	QPM	Ghana	1992
ZS261	QPM	Zimbabwe	2006
BHQP542	QPM	Ethiopia	2001
Q623	QPM	South Africa	2014
Yanrui-1	QPM	China	2010

QPM = quality protein maize

Biofortification

Nutrient supplementation and food fortification are two efficient techniques that help people to ensure a balanced diet. However, both strategies have limited access to most rural populations in developing countries (Kiran *et al.,* 2022). The biofortification method provides a more sustainable approach to defeat malnutrition (Wakeel and Labuschagne, 2021), as through plant breeding procedures, it delivers highly nutritious plants to the farmers with the necessary micronutrients for a balanced diet. So far, maize biofortification focuses on specific nutrients, such as zinc, provitamin A, lysine, and tryptophane (Prasanna *et al.,* 2020). A list of some provitamin A, zinc, and QPM biofortified maize varieties is available in Table 6 (Goredema-Matongera *et al.,* 2021).

The biofortification technique is very useful for developing countries, especially for the poorest ones that rely on few crops to feed most of their entire populations (Kiran *et al*., 2022). With a correct strategy, the nutrition of millions of people could be achievable with this approach. For this reason, it would be wise to implement this technique in Malaysia. However, before doing it, it would be worth considering the challenges seen in Southeast Africa, where micronutrient deficiency is complex and difficult to address with only one nutrient, and a multi-nutrient maize cultivar requires development.

For the case of Asia, Zunjare *et al*. (2018) developed a provitamin A version of QPM hybrids. In that respect, they selected four QPM hybrids produced in IARI (Indian Agricultural Research Institute), India; however, instead of replicating the exact crosses to develop them, they integrated into the equation a provitamin A donor crossed with both parental inbreds. The first sub-type came from a backcross 1-F1 (BC1F1), where the F1 between the donor parent and the recurrent parent underwent crossing again with one of the parents. The second sub-type came from a backcross 2-F1 (BC2F1), where the F1 of the previous backcross again attained crossing with the same parent. The third sub-type came from the selfing of the obtained offspring.

The experiment results demonstrated that the grain yield of the original and the reconstituted hybrids was quite similar, and even in two cases, the average of the reconstituted hybrids compared with its original version was a bit higher. However, a big difference between the original QPM hybrids and their reconstituted versions emerged concerning the provitamin A content, confirming that this method was successful in developing provitamin A-enhanced versions of the original QPM hybrids

(Zunjare *et al*., 2018). Furthermore, the impact of biofortification also depends on the efficient development of sustainable markets for biofortified seeds and products; hence, growers do not rely on just one market to deliver their nutritious products (Kiran *et al.,* 2022).

CONCLUSIONS

Considerable research has progressed to identify potential inbred combinations for specific conditions, sites, and stresses. However, it is necessary to understand the combining ability determination based on improving nutritional quality and integrating it with other vital agronomic traits. Educating growers and consumers and promoting the importance of a balanced and healthy diet is crucial. Finally, implementing this combining ability technique in maize breeding for developing countries, such as Malaysia, is imperative for sustaining food security, hence reducing the dependency on food imports.

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