

Variability of Agronomic Traits of Wheat (*Triticum aestivum* L.) Lines in Two Agroecosystems in Indonesia

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Abstract

Wheat is an important agricultural commodity in Indonesia, yet the country remains heavily reliant on imports to meet domestic demand. The diverse agroclimatic conditions in the highlands and lowlands pose significant challenges for national wheat production. This study aimed to evaluate the performance of wheat lines in two distinct altitude environments: Cipanas (1120 m above sea level) and Cisarua (600 m above sea level). An augmented randomized complete block design (RCBD) assessed 50 F6 wheat lines derived from the HP1744/"Selayar" cross. The results revealed significant variability in agronomic traits attributable to altitude differences. However, genotype-by-environment (G×E) interactions were found to be non-significant for all evaluated characters. Broad-sense heritability was classified as medium for the grain-filling period in Cipanas and seed weight of the main panicle in Cisarua, while all other traits exhibited low heritability. Based on the stress sensitivity index (SSI), 14 lines (28%) were identified as tolerant to the medium-altitude environment, which usually has higher temperatures than in the high-altitude. Particularly in terms of seed weight of the main panicle. These findings are of utmost importance as they underscore the need to consider genetic and environmental factors in developing wheat cultivars suitable for Indonesia's diverse agro-climatic conditions.

Keywords: augmented randomized complete block design, genetic x environment interaction, stress sensitivity index, "Selayar", tropical wheat

Introduction

Wheat (*Triticum aestivum* L.) is a staple food crop in Indonesia, yet the country remains heavily dependent

on imports to meet domestic demand. Despite the potential for local wheat production, Indonesia's agroclimatic conditions, particularly in the lowlands, pose significant challenges for optimal growth. According to the Central Statistics Agency (BPS, 2024), Indonesia imported an average of 10.5 million tons of wheat annually from 2017 to 2023. The average per capita wheat consumption in 2022 was 7.3 kg (Bappenas, 2022). Although wheat thrives in subtropical regions with temperatures ranging from 4°C to 25°C (Paudel et al., 2021), Indonesia's highlands, primarily used for plantation crops such as tea and coffee, offer limited opportunities for wheat cultivation. The lowlands, where most agricultural land is located, often experience higher temperatures that can adversely affect wheat production (Cao et al., 2015; Roy et al., 2021). Elevated temperatures accelerate crop maturity and reduce grain quality (Paudel et al., 2021).

Previous studies on wheat varieties introduced from India, Turkey, CIMMYT, and Indonesia (e.g., "Dewata" and "Selayar") have demonstrated that wheat cultivated in lowland areas (300 m above sea level) can yield between 34.8 and 454.76 g per plot, also found that HP1744 is an introduced accession with a shorter flowering period (Wahyu et al., 2013). The study also identified HP1744 as an introduced accession with a shorter flowering period, making it suitable for certain environments. In response to these challenges, the Indonesian government has intensified efforts to breed wheat varieties better adapted to tropical conditions. The Ministry of Agriculture has released several tropical wheat varieties, including "Dewata", "Nias", "Guri 1", "Guri 2", "Guri 3", and "Selayar", which show promising yield potential, particularly in the highlands.

Putri et al. (2020) initiated a breeding program focused on developing transgressive segregants to further improve wheat production in Indonesia.

By crossing tropical wheat varieties released in Indonesia, the program produced biparental pairs, with the HP1744/"Selayar" cross exhibiting the highest genetic variability coefficient. These materials formed the basis of the present study, which aims to evaluate agronomic traits, genetic parameters, genotype-environment interactions (GxE), and stress tolerance in F6 wheat lines derived from the HP1744/"Selayar" cross.

Material and Methods

Field experiments were conducted at two distinct Need space-bars: agroecosystems in Indonesia: the Cipanas Ornamental Plant Center Experimental Station in Cianjur (1120 m asl) and the farmers' field in Cisarua, Bogor (600 m asl). The trials spanned from April to September 2021. The genetic material consisted of 50 F6 wheat genotypes derived from the HP1744/"Selayar" cross, selected using the pedigree selection method. Four comparison varieties, namely "Guri 1" (G1), "Guri 2" (G2), "Guri 3" (G3), and "Selayar" (Se), were also included in the study. Other materials were fertilizers. Urea, SP-36, and KCl were applied at the rates of 200 kg.ha⁻¹, 200 kg.ha⁻¹, and 100 kg.ha⁻¹, respectively, and manure was applied at the rate of 10 tons.ha⁻¹. Pesticides were used according to the plant conditions in the field, and a Li-3000C Portable Leaf Area Meter was used to measure leaf area.

In each location, the experiment was arranged in an augmented randomized complete block design (augmented RCBD). The augmented RCBD was selected to address the challenge of having a limited number of seeds for the evaluated lines. In this design, control varieties are planted multiple times across all blocks. The controls are used for value corrections during data analysis, enhancing the reliability of the results. The augmented RCBD is used in which the number of replications is determined using the following formula:

$$r \geq \frac{10}{c-1} + 1;$$

where r = number of replications and c = number of comparisons. With four comparison varieties, there were 5 replications. The 50 evaluated lines were randomly planted within the five replications to create 70 experimental units. Each replication contains ten lines and four controls. Each line and control are planted in a plot measuring 1 m by 1.5 m, with a spacing of 30 cm between plants in a plot. Six plant samples were randomly selected from each plot, ensuring that edge plants were excluded from the sampling process.

A combined analysis of variance was carried out to obtain information on the interaction of genotype x environment (GxE) from the evaluated lines on the observed characters. Estimation of broad-sense heritability values was carried out using the following equation:

$$h_{bs}^2 = \frac{\sigma^2_g}{\sigma^2_p} \times 100\% ;$$

where h_{bs}^2 = broad-sense heritability, σ^2_g = genotypic variance, σ^2_p = phenotypic variance.

The stress sensitivity index (SSI) value was calculated using the following equation (Fischer and Maurer 1978):

$$SSI = (1 - Y_{is}/Y_{io}) / (1 - \bar{X}_{ts}/\bar{X}_{to})$$

where SSI = stress sensitivity index, Y_{is} = mean value of observed characters in the stressed area, Y_{io} = mean value of observed characters in the optimal area, \bar{X}_{ts} = mean value of observed characters for the population in the stressed area, \bar{X}_{to} = mean value of observed characters for the population in the optimal area. Genotypes are classified as tolerant (SSI < 0.5), moderate (0.5 < SSI < 1), and sensitive (SSI > 1) (Fischer and Maurer, 1978).

Observations were made on six plants or all plants for the following agronomic traits: (1) grain-filling period (GFL), (2) plant height (PH), (3) flag leaf area (FLA), (4) flag leaf width (FLW), (5) number of tillers per plant (NOT), (6) number of productive tillers (NPT), (7) number of seeds of the main panicle (NOS), (8) seed weight of the main panicle (SW). All data were collected and analyzed using SAS On Demand, RStudio using the "augmentedRCDB" package (Aravind et al., 2023) and MS Excel software. The Least Significant Difference (LSD) test was employed to determine significant differences among the genotypes evaluated at each location.

Result and Discussion

Performance of Agronomic Characters of Wheat Lines in Cisarua (600 m asl) and Cipanas (1120 m asl)

During the experiments, the average temperature in the medium altitude location (Cisarua) was 26.7 °C, with a maximum temperature of 33.6 °C and a minimum of 21°C. In contrast, the high-altitude location (Cipanas) had an average temperature of 21.4°C, with a minimum of 17.5°C and a maximum of 23.6°C. Additionally, Cisarua experienced higher average rainfall and humidity than Cipanas. Daily

Table 1. Average of agroclimatic components in Cisarua (600 m asl) and Cipanas (1120 m asl)

Agroclimatic components		Location	
		Cisarua	Cipanas
Temperature (°C)	Minimum	20.60	17.02
	Maximum	33.53	24.85
	Average	26.25	21.50
Rainfall (mm)	Average	359.82	181.18
Humidity (%)	Average	82.83	76.17
Sunshine hours (%)	Average	38.58	49.67

rainfall in Cisarua was nearly double that of Cipanas, while sunshine hours were recorded at 49.67% in Cisarua and 36.58% in Cipanas (Table 1).

Among 50 F6 wheat lines evaluated in Cipanas (1120 m asl), the following lines exhibited the most extended grain-filling period (GFP): HP/Se F2-80-2-6-16, HP/Se F2-74-5-10-14, HP/Se F2-127-4-1-17, and HP/Se F2-5-15-3-8 (62 days), where this value was not significantly different from the comparison varieties "Selayar", "Guri 1", "Guri 2", and "Guri 3".

The highest plant height (PH) was observed in the HP/Se F2-74-1-10-10 line, reaching 92.30 cm. The largest flag leaf area (FLA) and flag leaf width (FLW) were recorded in the HP/Se F2-80-2-6-10 line (38.91 cm²) and HP/Se F2-74-5-10-19 line (1.59 cm), respectively. Both of these values exceeded those of all comparison varieties.

The HP/Se F2-5-15-3-7 line demonstrated the highest number of tillers per plant (TN) and productive tillers (PTN), with values of 38.81 and 38.22, respectively. These values were superior to all comparison varieties.

Finally, the HP/Se F2-74-5-10-2 line had the highest seed number of the main panicle (SN) at 55.51, surpassing "Guri 1", "Guri 2", and "Selayar". The largest seed weight of the main panicle (SW) was found in the HP/Se F2-144-21-9-23 line (2.14 g), which was also greater than "Guri 1", "Guri 2", and "Selayar" (Table 2).

The evaluation of F6 wheat lines in Cisarua (600 m asl) revealed that the HP/Se F2-74-5-10-21 line exhibited the most extended grain-filling period (GFP) at 53 days. The highest plant height (PH) was recorded in the HP/Se F2-5-15-3-18 line, reaching 68.48 cm. The largest flag leaf area (FLA) and flag leaf width (FLW) were observed in the HP/Se F2-5-15-3-18 line (25.76 cm²) and HP/Se F2-102-3-10-17 line (1.31 cm), respectively.

The HP/Se F2-5-15-3-18 line also demonstrated the highest number of tillers per plant (TN) and productive tillers (PTN), with values of 24.35 and 21.55, respectively. The highest seed number of the main panicle (SN) was found in the HP/Se F2-127-4-1-17 line (50.77), while the highest seed weight of the main panicle (SW) was recorded in the HP/Se F2-127-4-1-15 line (1.90 g).

Notably, all lines with the highest agronomic characters in Cisarua (600 m asl) displayed superior values compared to all comparison varieties, except for the grain-filling period. Interestingly, the HP/Se F2-5-15-3-18 line is excellent in four traits: plant height (PH), flag leaf area (FLA), tiller number (TN), and productive tiller number (PTN). Furthermore, the main panicle's seed number and weight were comparable or even better than the comparison varieties (Table 3).

The findings of this study suggest that a decrease in altitude can lead to a reduction in the values of agronomic traits in tropical wheat plants. Previous research conducted by Nasution et al. (2019) in the Padang Sidempuan area, North Sumatra, Indonesia (700 m asl), reported plant heights of 55.00 cm, 47.83 cm, and 72.26 cm for the "Guri 1", "Guri 2", and "Guri 3" varieties, respectively. In the present study, the plant heights of these comparison varieties in Cisarua (600 m asl) were 52.11 cm, 51.96 cm, and 48.42 cm, respectively, while in Cipanas (1120 m asl) they were 57.74 cm, 63.95 cm, and 60.69 cm. These results align with those of Firmansah et al. (2024), who observed a decrease in the height of wheat plants in the lowlands compared to the highlands when studying convergent breeding lines derived from "Selayar", Oasis, Rabe, HP1774, Dewata, and Alibey varieties. Xu et al. (2021) attributed high-temperature stress to reduced photosynthesis due to decreased leaf chlorophyll content. This mechanism could explain the observed decrease in agronomic traits at lower altitudes in the present study.

Table 2. Performance of F6 wheat best lines for each character at Cipanas (1120 m asl)

Lines/varieties	GFP (days)	PH (cm)	FLA (cm ²)	FLW (cm)	TN	PTN	SN	SW (g)
HP/Se 80-2-6-16	62.00	83.87	24.98	1.49	35.72	34.80	50.17	1.98
HP/Se 74-5-10-14	62.00	88.18	27.78	1.44	36.94	31.52	46.99	1.95
HP/Se 127-4-1-17	62.00	90.30	28.22	1.48	26.49	23.89	43.74	1.80
HP/Se 5-15-3-8	62.00	82.47	23.28	1.50	26.11	23.19	39.99	1.57
HP/Se 74-5-10-10	59.00	92.30	32.38	1.46	31.93	28.76	48.48	1.92
HP/Se 80-2-6-10	61.00	84.05	38.91	1.33	26.02	25.14	40.23	1.66
HP/Se 74-5-10-19	58.00	88.12	33.78	1.59	26.90	25.07	53.94	2.04
HP/Se 5-15-3-7	57.00	85.12	21.10	1.38	38.81	38.22	51.42	2.13
HP/Se 74-5-10-2	51.00	84.62	23.58	1.44	29.39	25.50	55.51	2.08
HP/Se 144-21-9-23	59.00	82.10	22.56	1.34	29.94	26.13	49.96	2.14
G1 ("Guri 1")	57.74	83.63	22.56	1.40	25.42	23.16	46.70	1.87
G2 ("Guri 2")	63.95	81.62	24.65	1.22	29.57	27.33	47.41	1.49
G3 ("Guri 3")	60.69	101.89	27.71	1.29	32.97	31.64	59.52	1.90
Se ("Selayar")	57.82	72.66	28.47	1.31	25.63	24.99	54.96	2.27
LSD α 0.05	11.00	72.66	24.01	1.26	18.77	19.54	40.79	1.50

Notes: GFP= grain filling period; PH= plant height; FLA= flag leaf area; LFW= flag leaf width; TN= tiller number per plant; PTN= productive tillers number; SN= seeds number of the main panicle; SW= seed weight of the main panicle. The values in bold are the best for each character.

Table 3. Performance of F6 wheat best lines for each character at Cisarua (600 m asl)

Lines/varieties	GFP (days)	PH (cm)	FLA (cm ²)	FLW (cm)	TN	PTN	SN	SW (g)
HP/Se 74-5-10-21	53.00	53.56	15.18	0.99	12.18	10.21	40.59	1.61
HP/Se 5-15-3-18	50.00	68.48	25.76	1.25	24.35	21.55	43.04	1.68
HP/Se 5-15-3-4	48.00	51.40	9.78	1.08	11.32	8.13	34.35	1.33
HP/Se 102-3-10-17	51.00	59.14	14.35	1.31	09.68	7.96	42.76	1.67
HP/Se 127-4-1-17	47.00	67.62	20.16	1.21	19.20	14.83	50.77	1.58
HP/Se 127-4-1-15	46.00	61.39	21.89	1.04	16.42	14.45	48.33	1.90
G1 ("Guri 1")	52.11	51.55	16.60	0.81	7.12	6.07	38.31	1.07
G2 ("Guri 2")	51.96	51.53	13.73	0.85	12.59	10.03	41.94	1.29
G3 ("Guri 3")	48.42	65.92	18.04	0.90	16.74	12.64	43.08	1.60
Se ("Selayar")	54.42	42.77	10.39	0.81	7.58	7.13	21.46	0.83
LSD α 0.05	19.32	24.93	17.13	0.44	14.81	14.21	23.00	0.74

Notes: GFP= grain filling period; PH= plant height; FLA= flag leaf area; LFW= flag leaf width; TN= tiller number per plant; PTN= productive tillers number; SN= seeds number of the main panicle; SW= seed weight of the main panicle. The values in bold are the best for each character.

The grain-filling period is a critical stage in wheat production, and stress during this phase can significantly reduce yield due to decreased carbohydrate metabolism (Miroslavljević et al., 2021), reduced photosynthesis rate, and increased damage to the thylakoid membrane (Djanaguiraman et al., 2020). A shorter grain-filling period can result in reduced fresh and dry weight of seeds and decreased seed size (Hurkman et al., 2009).

Zhang et al. (2022) found that a decrease in accumulated solar radiation and an increase in temperature due to differences in altitude can lead to a decrease in spring wheat yield by 0.27 tons/ha. Similarly, in the present study, the lower location (Cisarua) experienced shorter sunshine hours and higher temperatures, contributing to lower production. Excessive rainfall can also negatively impact wheat production by triggering diseases such as leaf rust

and Fusarium-related diseases (Le Gouis et al., 2020). Additionally, high rainfall can lead to nitrogen leaching in the soil (Guinet et al., 2020). Research on winter wheat has shown a decrease in yield of 18.4% due to excessive rainfall (Liu et al., 2021). The phenomenon of decreased yields due to heavy rain and low solar radiation has been observed in France in 2016 (Nóia Júnior et al., 2023). These factors may also contribute to the present study's lower agronomic character values observed in Cisarua (600 m asl) compared to Cipanas (1120 m asl).

Broad-sense Heritability Values and G x E Interactions of Wheat Lines in the Two Environments

The broad-sense heritability values for the grain-filling period (GFP) and flag leaf area (FLA) in Cipanas (1120 m asl) were 37.58% and 4.98%, respectively (Table 4). For the traits of tillers number per plant (TN), seed number of the main panicle (SN), and seed weight of the main panicle (SW) in Cisarua (600 m asl), the heritability values were 0.81%, 14.23%, and 37.50%, respectively (Table 5). Notably, the broad-sense heritability of all other characters in Cipanas and Cisarua was zero due to negative genetic variance.

Heritability values can be used to estimate the proportion of phenotypic variation influenced by genetic factors (Shavkiev et al., 2021). The broad-sense heritability categories are as follows: high ($h^2_{bs} \geq 50\%$), moderate ($20 \geq h^2_{bs} \geq 50\%$), and low ($h^2_{bs} \leq 20\%$) (Hakim et al., 2019). The low and moderate heritability values observed in this study indicate that environmental factors are more significant than genetic factors in determining phenotypic variation. The non-significant GxE interactions and the significant environmental effects further support this conclusion.

The combined analysis of variance for Cisarua (600 m asl) and Cipanas (1120 m asl) revealed that GxE interactions were not significant for any of the traits. This suggests that a superior genotype in one location tends to remain superior in the other (Jayaningsih et al., 2020). Non-significant GxE interactions also indicate that the genotypes are relatively stable (Karuniawan et al., 2021). However, GxE results can be inaccurate if there are biases in the study, such as low broad-sense heritability values, low genetic correlation values, or small family sizes (Sae-Lim et al., 2010).

Table 4. Estimated values of variance and broad-sense heritability of F6 wheat lines in Cipanas (1120 m asl)

Character	σ^2_e	σ^2_p	σ^2_g	h^2_{bs} (%) - category
GFP (grain filling period, days)	11.41	18.28	6.87	37.58 - M
PH (plant height, cm)	22.26	6.21	-16.05	0.00 - L
FLA (flag leaf area, cm ²)	11.85	12.47	0.62	4.98 - L
FLW (flag leaf width, cm)	0.01	0.01	0.00	0.00 - L
TN (tiller number per plant)	33.22	15.31	-17.91	0.00 - L
PTN (productive tiller number)	35.97	14.14	-21.83	0.00 - L
SN (seed number of the main panicle)	34.92	23.82	-11.10	0.00 - L
SW (seed weight of the main panicle, g)	0.09	0.04	-0.05	0.00 - L

Notes: σ^2_e = environmental variance, σ^2_p = phenotypic variance, σ^2_g = genotypic variance, h^2_{bs} = broad-sense heritability, M = medium, L = low. Negative genotypic variance is assessed as zero in subsequent calculations.

Table 5. Estimated values of variance and broad-sense heritability of F6 wheat lines in Cisarua (600 m asl)

Character	σ^2_e	σ^2_p	σ^2_g	h^2_{bs} (%) - category
GFP (grain filling period, days)	35.19	5.90	-29.29	0.00 - L
PH (plant height, cm)	58.61	24.23	-34.38	0.00 - L
FLA (flag leaf area, cm ²)	27.67	13.11	-14.56	0.00 - L
FLW (flag leaf width, cm)	0.02	0.02	0.00	0.00 - L
TN (tiller number per plant)	20.66	20.83	0.17	0.81 - L
PTN (productive tiller number)	19.03	15.36	-3.67	0.00 - L
SN (seed number of the main panicle)	49.85	58.12	8.27	14.23 - L
SW (seed weight of the main panicle, g)	0.05	0.08	0.03	37.50 - M

Notes: σ^2_e = environmental variance, σ^2_p = phenotypic variance, σ^2_g = genotypic variance, h^2_{bs} = broad-sense heritability, M = medium, L = low. Negative genotypic variance is assessed as zero in subsequent calculations.

Table 6. Analysis of variance combined genotype (G), environment (E) and GxE interactions of agronomic characters of wheat lines

Character	Mean square		
	G	E	GxE
GFP (grain filling period, days)	13.11 ^{ns}	2746.62 ^{**}	12.72 ^{ns}
PH (plant height, cm)	19.70 ^{ns}	29882.10 ^{**}	15.80 ^{ns}
FLA (flag leaf area, cm ²)	16.60 ^{ns}	3781.00 ^{**}	10.60 ^{ns}
FLW (flag leaf width, cm)	0.01 ^{ns}	5.73 ^{**}	0.01 ^{ns}
TN (tiller number per plant)	18.80 ^{ns}	9832.40 ^{**}	16.60 ^{ns}
PTN (productive tiller number)	13.30 ^{ns}	9958.80 ^{**}	15.30 ^{ns}
SN (seed number of the main panicle)	43.30 ^{ns}	4059.50 ^{**}	44.80 ^{ns}
SW (seed weight of the main panicle, g)	0.05 ^{ns}	7.83 ^{**}	0.64 ^{ns}

Notes: **= significant at $\alpha=0.01$, ns= not significant at $\alpha=0.05$

Table 7. Recapitulation of stress sensitivity index (SSI) categories of F6 wheat lines according to agronomic characters

Tolerance category	SSI criteria characters							
	GFP (days)	PH (cm)	FLA (cm ²)	FLW (cm)	TN	PTN	SN	SW (g)
	Number of wheat lines (%)							
Tolerant	9 (18)	0 (0)	8 (16)	5 (10)	4 (8)	4 (8)	15 (30)	14 (28)
Moderate	15 (30)	28 (56)	20 (40)	21 (42)	25 (50)	21 (42)	10 (20)	10 (20)
Sensitive	26 (52)	22 (44)	22 (44)	24 (48)	21 (42)	25 (50)	25 (50)	26 (52)

Notes: GFP= grain filling period; PH= plant height; FLA= flag leaf area; LFW= flag leaf width; TN= tiller number per plant; PTN= productive tillers number; SN= seeds number of the main panicle; SW= seed weight of the main panicle.

In this study, the genetic material originated from a single biparental cross (HP1774 and "Selayar"), which may have contributed to the non-significant GxE interactions due to the similar responses of the lines in both locations.

Stress Sensitivity Index (SSI) Values of Wheat Lines

The number of lines categorized as tolerant based on the observed agronomic characteristics ranged from 0 to 15 lines, representing 0% to 30% of all lines evaluated. No lines were classified as tolerant in terms of plant height. In contrast, 42% to 52% of the lines were sensitive to stress caused by differences in planting location altitude, while the remaining lines were categorized as moderately tolerant based on the Stress Sensitivity Index (SSI). When considering the seed weight of the main panicle (SW) trait, 14 genotypes (28% of all genotypes) were identified as tolerant to stress (Table 7).

Abiotic stress can disrupt plant physiological processes, including carbon assimilation, transpiration rates, and photosynthesis (Demirel et al., 2020). The SSI is a valuable index for selecting wheat lines capable of thriving in stressful environments, with a lower SSI value indicating a higher level of stress tolerance (Anwaar et al., 2020). Poudel et al. (2021) found a negative correlation between SSI and production yields, suggesting that higher SSI values are associated with lower yields.

Conclusion

This study demonstrates significant variability in agronomic traits among wheat lines derived from the HP1744/"Selayar" cross when evaluated in two distinct agroecosystems in Indonesia. Broad-sense heritability values for agronomic characteristics differed between the two locations, with the predominance of medium and low heritability indicating that environmental factors have a more

significant influence on phenotypic variation than genetic factors. Genotype-by-environment (GxE) interactions were non-significant, likely due to high environmental variability and limited genetic variation within the study materials. Please revise the sentence to be: Fourteen lines were identified as tolerant to the medium-altitude environment, which usually has higher temperatures than in the high-altitude. medium-altitude environment based on their SSI values for the seed weight of the main panicle. These findings underscore the importance of considering genetic and environmental factors when developing wheat cultivars suited to Indonesia's specific agro-climatic conditions. Future research should focus on increasing the genetic diversity of breeding populations and exploring targeted breeding strategies to enhance stress tolerance and improve agronomic performance in tropical environments.

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