

Yield Stability of Indonesian Coffee Production - Comparison Between Arabica and Robusta

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ABSTRACT

Coffee is a significant commodity in Indonesia, and the two most widely cultivated coffee species are Arabica (*Coffea arabica*) and Robusta (*Coffea canephora*). This study aims to compare the yield stability of Arabica and Robusta coffee in Indonesia, and the performance of regions from the viewpoint of yield stability. Using the Yield Stability Index, the study measures yield stability over 10-years (2011-2020) using data from the Directorate General of Estates, Ministry of Agriculture. The Yield Stability Index is based on the comparison of yield fluctuations to fluctuations produced by normally distributed yield series. Results show, that the two coffee species considerably differ in their stabilities, and the stability of yields across regions also shows large discrepancies. While Robusta yields were stable in all the 33 analyzed regions, though to a different extent, for Arabica, produced in 20 regions, only 4 could produce stable yields. The yield stability of Indonesian coffee is influenced by a complex interplay of environmental factors, agronomic, and socio-economic factors. Mitigating these yield stability challenges requires a multifaceted approach.

Key words: Arabica; robusta; Indonesian Coffee Yield; normal distribution; yield stability index.

1 INTRODUCTION

Indonesia is one of the world's leading coffee producers and exporters, known for its diverse range of coffee species (Tenriawaru et al., 2020). With approximately 1.2 million hectares dedicated to coffee cultivation, Indonesia ranks as the fourth-largest coffee producer in the world (Rahmawati; Chumaidiyah, 2020). Coffee production is important for the country's economy and generates a significant portion of its foreign exchange earnings and rural livelihoods. Indonesia's coffee industry generated approximately 1.17 billion USD in foreign exchange in 2017, although it faced fluctuations in production and trade performance (Okim; Hanani; Syafrial, 2022). However, coffee production in Indonesia is susceptible to various environmental factors, which may cause fluctuation in yield (Harsono; Wibowo; Supriyanto, 2021). Therefore, understanding the yield stability of different coffee species is critical to the development of sustainable coffee production.

Indonesia is known for producing a diverse range of coffee species, each with its unique flavor profile. Eighty-two percent of Indonesia's coffee plantation area is dominated by Robusta coffee, while the remaining 18% is Arabica coffee (Harsono; Wibowo; Supriyanto, 2021; Rahmawati; Chumaidiyah, 2020; Summase et al., 2020; Tenriawaru et al., 2020). The country has several regions with soil conditions and ideal climates that are suitable for cultivating coffee plants, including Arabica and Robusta species (Grüter et al., 2022). Arabica coffee, which is generally considered to be of higher

quality than Robusta, is grown mainly in the highland regions (Hidayat et al., 2020; Vionita; Kardhinata; Damanik, 2021) of Aceh, North Sumatra, Central Java, East Java, Bali, and Papua. The Arabica species is favored for its delicate flavor, acidity, and aroma (Marsilani, Wagiman; Sukartiko, 2020). However, Arabica is also more susceptible to diseases and pests and requires more care and attention compared to Robusta (De Almeida et al., 2021; Shimaes et al., 2023; Zewdie et al., 2023). Robusta coffee, on the other hand, is typically grown in lowland regions (Marsilani; Wagiman; Sukartiko, 2020; Harsono; Wibowo; Supriyanto, 2021) of Sumatra, Celebes, Java, and Borneo. Robusta beans are bitter and have a stronger flavor than Arabica (Privat et al., 2008; Bicho et al., 2011; Vega et al., 2020; Šeremet et al., 2022). Robusta is also generally easier to grow and more resistant to pests and diseases than Arabica (Tavares et al., 2023). In addition to these two main species, Indonesia is also home to unique coffee such as Kopi Luwak or civet coffee (Campera et al., 2021) and Toraja Sulawesi (Laksono et al., 2022), which are highly valued in the international coffee market. The diversity of coffee species in Indonesia reflects the country's rich coffee culture and heritage.

Indonesia's coffee production is supported by a diverse array of producers, including smallholder farmers, government-owned plantations, and private estates. Smallholder farmers constitute the backbone of the industry, responsible for nearly 99% of the nation's coffee output (Acosta-Alba et al., 2020). Typically operating on plots smaller than two hectares (Vogel

et al., 2023), these farmers rely on coffee as a primary cash crop (Duffy et al., 2021) and employ traditional, low-cost cultivation methods (Borrelli; Mataix; Carrasco-Gallego, 2015). However, smallholder farmers often face significant limitations, including restricted access to financing, advanced technology (Putra; Budisusanto; Deviantari, 2022), and critical market information (Candelo et al., 2018), which can constrain both yield and quality.

In contrast, government and private plantations, although contributing a smaller share to total production, tend to be better equipped with resources (Setyoningtyas; Darmawati; Sutrisno, 2022). Government-managed estates, primarily operated by the state-owned enterprise PT Perkebunan Nusantara (PTPN), and private plantations benefit from more substantial financial and technological support. These plantations generally utilize advanced cultivation techniques and have better access to credit, insurance, and market data, factors that can enhance yield stability and coffee quality.

Despite the disparity in resources, all three types of producers play a critical role in Indonesia's coffee sector. Smallholder farmers are instrumental not only in production volume (Rosiana; Feryanto, 2022) but also in the cultivation of specialty coffees (Rosyihuddin; Sudarmiatin; Bidhin, 2024) that attract significant demand in international markets. Conversely, government and private plantations largely contribute to the supply of commercial-grade coffee for the domestic market (Ashardiono; Trihartono, 2024).

Coffee farming has undergone significant changes in recent years, with farmers adopting various technologies to improve their yields and sustainability, particularly through climate-smart agricultural practices (Diro; Tesfaye; Erko, 2022) and modern technological innovations (Sott et al., 2020). These approaches not only improve productivity but also address environmental challenges depending on the type of coffee being grown, whether Arabica or Robusta, including improved seed varieties (Hasibuan et al., 2022), such as those that are resistant to certain diseases, can also help to improve yield and resilience.

Yield instability is a major cause of risk for farmers, as yields may vary from year to year, due to weather, pests, and management changes. This instability may be minimized by the choice of a proper production technology that includes proper choice of variety that is best suited to the local weather and environmental conditions. The proper farming technology should achieve high crop yields, but unfortunately, high yields often generate higher annual fluctuations in yields, too (Khalili; Pour-Aboughadareh, 2016; Nielsen; Vigil, 2018). The concept of reasonably stable yield means, that the deviation of the annual yield from an expected yield trend over time is small. When actual yields deviate greatly from the expected value, this creates a serious risk for the farmer.

Farm viability, therefore, requires, that deviations should be rare and of a limited magnitude. High yields are often related to higher yield variability and thus the evaluation of yield stability should take into account both the average yield and the variability of the yield, especially the risk of a yield falling below a certain limit, and not only the general level of yield variances (Piepho, 1998).

Different dispersion indicators are typically used to measure the time series fluctuation around the trend, and standard deviation of the data, or the standard deviation of crop yields, is the most widely used technique to evaluate crop yield stability (see e.g., Kamidi, 2001). Other applied techniques are the average percent deviation from a trend, whether it be linear or non-linear (Cuddy; Valle, 1978; Piepho, 1998). Empirical studies to assess yield stability have applied a range of indicators, including the sum of the squared difference or percentage between actual and baseline yield over time (Bracho-Mujica; Hayman; Ostendorf, 2019; Devkota et al., 2019); squared sums of differences between actual annual yields and average yields (Madembo; Mhlanga; Thierfelder, 2020; Howarth et al., 2021); and yield standard deviations (Assefa et al., 2021), mean square deviation from a fitted regression trend (Khalili; Pour-Aboughadareh, 2016), or the ratio of the residual values to the estimated trend values (Xiang et al., 2012). The common feature of these assessments is that they add up small and large fluctuations alike, arriving at an overall measure of variance. However, rare, but extreme fluctuations, especially extremely low values, pose a more severe situation for farmers than many minor ones (Piepho, 1998; Bacsı; Fekete-Farkas; Ma'ruf, 2022). Therefore, the present research applies a yield stability index that measures the risk of extreme fluctuations, and not the small ones, even if these latter are frequent.

This study seeks to further explore yield stability with the Yield Stability Index (YSI) – as explained in the Material and Methods section - across different types of coffee producers in Indonesia, with a specific focus on the differences between Arabica and Robusta species. Although the YSI methodology has been applied for the main coffee producing countries, it has not been computed for sub-national regions, nor for Arabica and Robusta separately. Thus the novelty of the present study is to reveal how sub-national regions, coffee types, and producer types (smallholders and large farmers) differ in terms of their yield stabilities, and their resilience in response to the external environment of the coffee sector.

2 MATERIAL AND METHODS

Yield stability can be measured in various ways, the core concept behind these is to compare the periodical variations of the yield to an average value or to an average trend. Yield stability is often computed by comparing the actual yield

deviations of each year from the average yield. In the present research the Yield Stability index developed by Bacsí and Vizvári (2002) and Vizvári and Bacsí (2002) is applied. The yield stability index for each species is calculated for 10-years (2011-2020) by using secondary data Directorate General of Estates, Ministry of Agriculture. Due to the limited availability of obtained power, the analysis was adjusted to the acquired data: 1. Coffee yield based on farming category by province; 2 - Arabica coffee yield by province; 3 - Arabica coffee yield of smallholder by province; 4 - Robusta coffee yield by province; and 5 - Robusta coffee yield of smallholder by province.

The distribution and production of Arabica and Robusta coffee species can be observed in Figures 1 and 2.

Based on Figures 1 and 2, Sumatra Island is identified as the primary coffee-producing region in Indonesia. Approximately 70% of Indonesia's coffee is produced on Sumatra, followed by Java Island, contributing around 12%, and Sulawesi Island and the Lesser Sunda Islands, each accounting for about 6% of the country's coffee production. The main production centers for Arabica coffee are North Sumatra, Aceh, and South Sulawesi provinces, contributing 32.60%, 32.15%, and 12.57%, respectively, while other provinces contribute less than 10%. In contrast, the primary production areas for Robusta coffee are South Sumatra, Lampung, and Bengkulu provinces, contributing 36.15%, 21.32%, and 11.13%, respectively, with other provinces contributing less than 10%.

2.1 Methodology of computing the Yield Stability Index (YSI)

The stability of coffee yields is analysed by applying the Yield Stability Index (YSI) developed by Bacsí and Vizvári (2002) and Vizvári and Bacsí (2002) in a way that the index can distinguish between few but rather large fluctuations of a time series, and frequent but small fluctuations. Regarding crop yields, the former may create an unacceptable risk for the farmer, while the latter might not, creating little risk. The YSI developed by Bacsí and Vizvári (2002) and Vizvári and Bacsí (2002) measures the occurrence of extremely high or low yields, and then quantifies the proportion of annual yields being reasonably close to the yield trend within a given time. This index was adjusted and tested by Bacsí and Hollósy (2019a, 2019b) for European crop yields of long periods, and by Bacsí, Fekete-Farkas and Ma'ruf (2022), to assess coffee yield stability worldwide. The present paper applies the same tool for assessing regional coffee yields in Indonesia for 33 regions and for two coffee species (Arabica and Robusta). The value of the Yield Stability Index (YSI) was computed for each region, and for each species, and also for total production, and separately for smallholder production, for ten years, from 2011 to 2020. The larger the index, the more stable (i.e. less fluctuating) the crop in the given time. The term 'weakly technologized crop' was applied to crops with negative YSI values (i.e. those showing large fluctuations during the analysed periods by Vizvári and Bacsí (2002) and Bacsí and Hollósy (2019a, 2019b)).

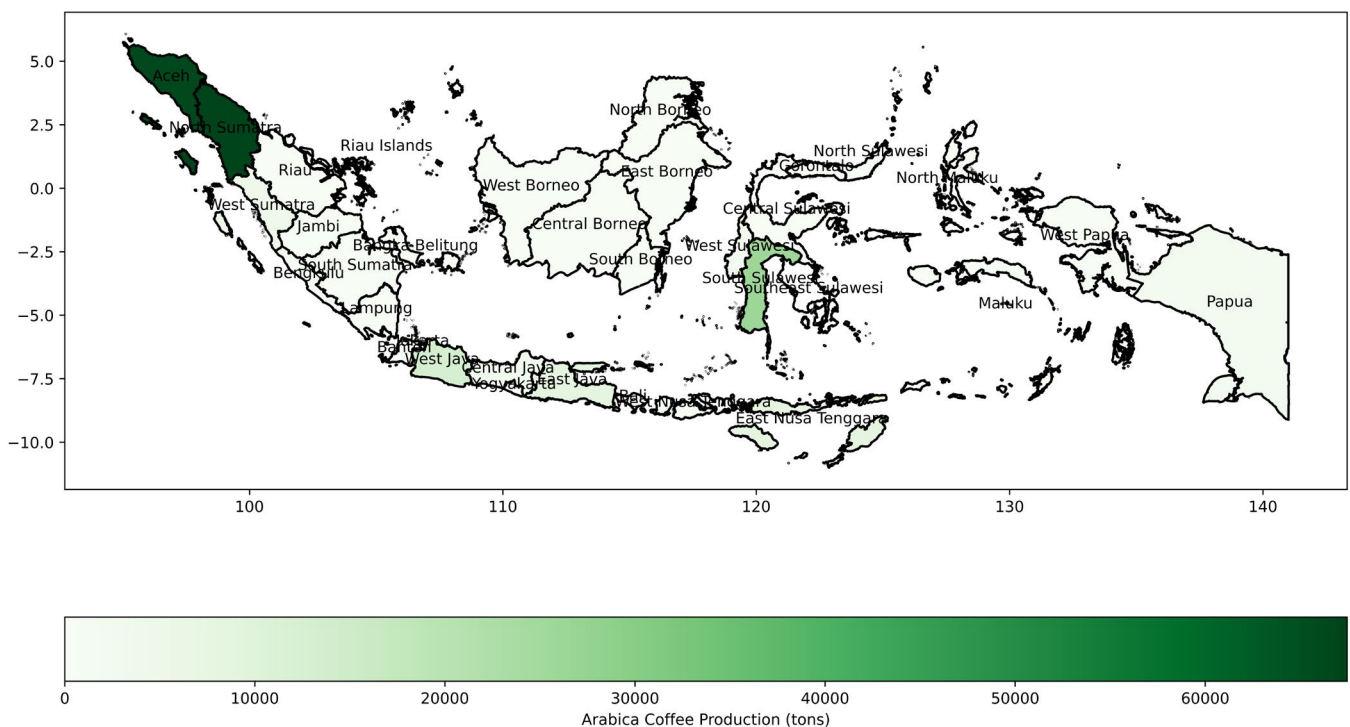


Figure 1: Distribution and Production of Arabica Coffee in Indonesia (color indicates level of production).

Source: Author's own computation (2024) using data from Directorate General of Estates, Ministry of Agriculture.

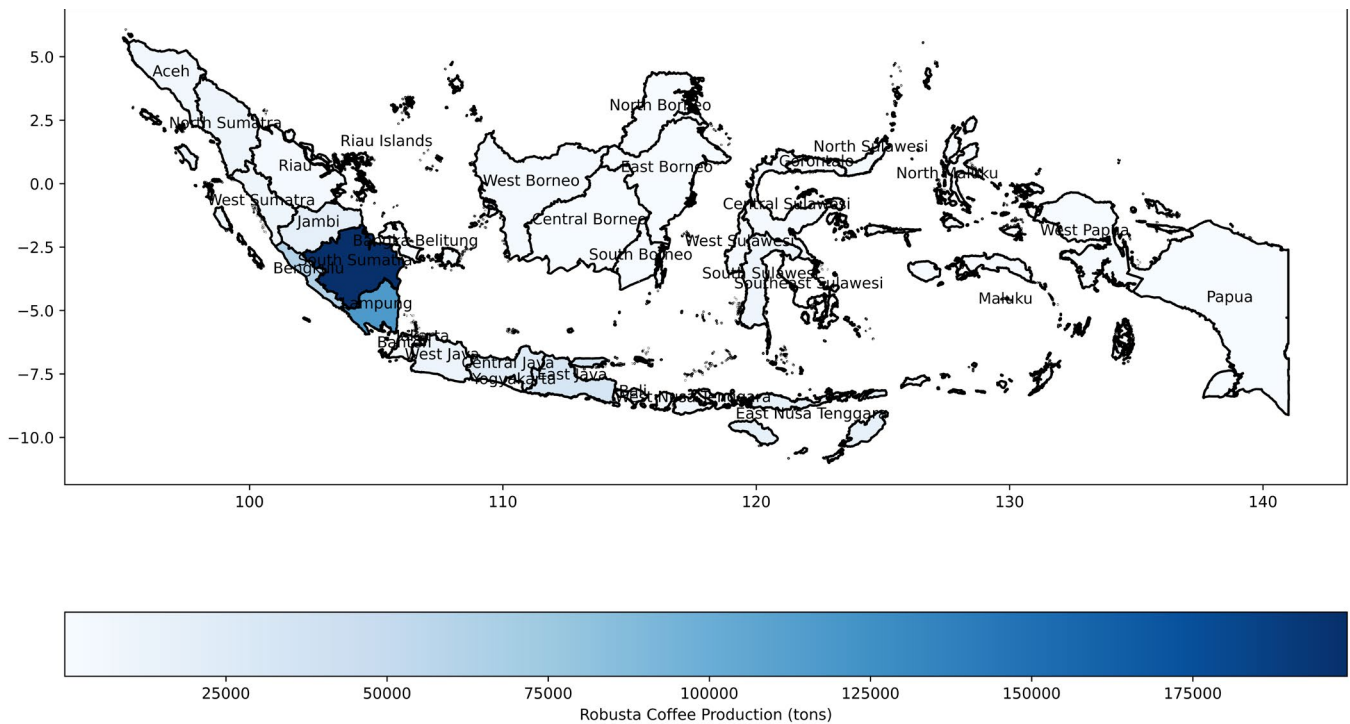


Figure 2: Distribution and Production of Robusta Coffee in Indonesia (color indicates level of production).

Source: Author's own computation (2024) using data from Directorate General of Estates, Ministry of Agriculture.

Hereby we briefly summarise the computation of the Yield Stability index (YSI), according to the methodology devised by Vizvári and Bacsí (2002), and revised by Bacsí and Hollósy (2019a, 2019b). As the study aims at comparing YSI values specifically for smallholders, and for Arabica and Robusta, and for various regions of Indonesia, YSI is computed separately with yield series for these.

Yield stability is measured from the annual yields recorded over a given period of years. The yield values are first divided by the series average, thus yields are expressed as in proportion to the average, thus the magnitude of fluctuations is evaluated in comparison to the mean yield. Then a linear regression line is fitted to the rescaled yield series, and this line can represent the mean trend of yield growth over time. Yield fluctuations are calculated as the differences between the observed rescaled yields and the respective linear trend values. These difference values give the residual series. The residuals will be compared to a normal distribution of the same variance. The range of residual values is divided into 10 equal segments (deciles). The proportion of the residuals falling into these segments is computed, and similarly, the distribution of the normal distribution of the same range is used to compute the expected proportion of a series derived from this normal distribution. The observed residual series are considered to have large fluctuations if many residual values are far from zero, i.e., when many residual values fall into the lowest three or highest three deciles. The term “many” is defined here as

“more than for the series derived from the normal distribution”. Thus taking the number of values falling in each segment from the observed residual series and from the normally distributed series, and the difference of observed and normal values is computed. Favourable differences are those that are positive for the central 6 segments, or negative for the smallest 3 segments and the largest 3 ones. Unfavourable differences are the opposite. The YSI is computed by subtracting the sum of unfavourable differences from the sum of favourable differences. The computation method gives an index that is directly comparable for periods of different lengths and crops with different magnitudes of mean yields.

When we have several regions for the analysis, to make the index values comparable for each of them, the parameters of the comparative normal distribution should be fixed. This is done by taking the absolute minimum and maximum values of the areas for defining the range of the normal distribution, and the average of the standard deviations of the residual series of each area, as was done in Bacsí, Fekete-Farkas and Ma'ruf (2022).

The computation algorithm of the YSI value is described by the following 9 steps:

1. x : the crop yield for region i , and year t , for $i = 1 \dots M$ regions and $t = 1 \dots N$ years
2. Then for each region $i = 1 \dots M$:
 - 2.a. $\bar{x}_i = (\sum_{t=1}^N x_{it}) / N$ the average crop yield for region i , during the time period $t = 1 \dots N$

- 2.b. $y_{it} = x_{it}/x_{it}^{IA}$ the crop yield for region i , and year t expressed as a proportion of the mean yield
- 2.c. a linear regression line is fitted to the y_{it} crop yield series, and its equation is $z_{it} = A \times t + B$, where z_{it} is the estimated value of at time t .
- 2.d. $r_{it} = y_{it} - z_{it}$ is the residual series for region i , and year t
- 2.e. s_i is the standard deviation of the residual series r_{it} for $t = 1 \dots N$, for region i .
3. $s = (\sum_{i=1}^M s_i)/M$, the average value of the regionwise standard deviations
4. $N(0,s)$ is the normal distribution of zero mean and s standard deviation, and $F(u)$ is the value of its distribution function at u , i.e., $F(u) = P(x < u; \text{ when } x \text{ is a value taken from } N(0,s))$
5. $MAX = \max\{r_{it} \mid t = 1 \dots N; i = 1 \dots M\}$ and $MIN = \min\{r_{it} \mid t = 1 \dots N; i = 1 \dots M\}$, and $d = (MAX - MIN)/10$
6. We define 10 intervals as: $I = [MIN + (j-1) \times d; MIN + j \times d)$, $j = 1 \dots 10$ (where $MIN + 10d = MAX$)
7. The 'favorable' intervals are I_1, I_2, I_3 , and I_7 , the 'unfavorable' intervals are $I_4, I_5, I_6, I_8, I_9, I_{10}$
8. For a series taken randomly from the normal distribution $N(0,s)$ the proportion of the values falling into the 'favorable' intervals is: $f_{nf} = F(MIN + 7d) - F(MIN + 3d)$, where F is the distribution function mentioned in 4.
9. Then for each region $i = 1 \dots M$:
The proportion of the r_{it} values falling into the 'favorable' intervals is:
 $f_{if} = 1/N \times \{\text{count of } r_{it} \mid t = 1 \dots N, \text{ for which } MIN + 3d \leq r_{it} < MIN + 7d\}$ and
 $YSI_i = 2 \times (f_{if} - f_{nf})$.

It is worth mentioning that YSI, as a stability measure, leads to considerably different conclusions than the methods based on simple standard deviation, which cannot distinguish between small and large fluctuations in assessing stability, while YSI can (Bacsi; Fekete-Farkas; Ma'ruf, 2022).

3 RESULTS

Following the computation method described above, Table 1 contains the yield stability index values for the Robusta and Arabica species. The Total-YSI refers to the combined YSI value for both Arabica and Robusta coffee, encompassing production managed by government estates, private estates, and smallholders. Smallh-YSI represents the combined YSI value for Arabica and Robusta coffee exclusively managed by smallholders. Rob-YSI denotes the YSI value for Robusta coffee under all management types (government estates, private estates, and smallholders), while Arab-YSI represents the YSI value specifically for Arabica coffee.

Table 2 presents the 10-year average yields per hectare for the regions, farm type and coffee species.

As it was described in the Methodology section, positive YSI values indicate stable yields, i.e. production technology well adapted to the local environmental conditions, while negative values indicate unstable yields, i.e. weakly adapted technology. As Table 1 indicates, Indonesia shows considerable stability for the total production (YSI=0.1579), and also for smallholders (YSI=0.1571, and for Robusta producers (YSI=0.0342). However, for Arabica, its yields seem to be rather unstable (YSI=-0.1599). Smallholder yield stability is somewhat smaller, than total stability, suggesting, that large producers can achieve somewhat more stable yields than smallholders. The various regions differ substantially, though the above seems to be a regular pattern for most of the regions. The negative YSI values for Arabica are typical for most of the regions, which might be due to the sensitivity of the Arabica species compared to the Robusta one. The only exceptions are Lampung and West Java, where YSI is positive not only for the Robusta, but the Arabica yields, too, and Bangka Belitung, where the Arabica yield series are the only stable series. The regions can also be grouped according to their stability types: regarding the total production besides the country as a whole, 21 regions have positive YSI values, for smallholder yields this figure is 22, for the Robusta species the whole of the country, and 23 regions have positive YSI values, but for Arabica only 4 regions show stable yields, and the country as a whole does not. Figure 3 shows the values by type of production and by region.

As the Figure 3 shows, most of the regions have very similar stability index values for the total and for the smallholder yields, which may be due to the fact that smallholders give the largest share of total production. The figure also clearly indicates that Robusta is a much more stable crop than Arabica.

Figure 4 demonstrates the relationship between average yield and yield stability. As it was mentioned previously (Khalili; Pour-Aboughadareh, 2016; Nielsen; Vigil, 2018), higher yields are generally associated with less stability, but our results do not support this opinion. The correlation coefficients between average yields and YSI values are 0.604 for Total, 0.616 for SmallH, 0.533 for Rob, and 0.143 for Arab, i.e. all correlations are positive, though the last one is very weak. Smallholder YSI aligns closely with the average yield for Total YSI. This can once again be interpreted as smallholders representing the predominant type of coffee cultivation in Indonesia. Comparing average yields with YSI for smallholders, yield levels above 600 kg/ha are mostly stable (YSI>0). Additionally, when comparing Arabica and Robusta coffee, it is evident, that when the average yield of Robusta coffee is less than 400 kg/ha, it is unstable, with mostly negative YSI values, while with higher yields positive YSI values prevail, indicating yield stability. For Arabica coffee the average yield levels are associated mostly with negative YSI values, indicating rather unstable production. There are still

Table 1: Yield Stability Index (YSI) Values for Total Coffee, Smallholder Coffee, Robusta Coffee, and Arabica Coffee in Indonesia.

No	Provinces	TOTAL-YSI	SMALLH-YSI	ROB-YSI	ARAB-YSI
1	Aceh	0.1579	0.1571	0.0342	-0.1509
2	North Sumatra	0.1579	0.1571	0.0342	-0.1509
3	West Sumatra	0.1579	0.1571	0.0342	-0.1509
4	Riau	0.1579	0.1571	0.0342	
5	Jambi	0.0263	0.0262	0.0057	-0.0509
6	South Sumatra	-0.0421	-0.0429	0.0342	
7	Bengkulu	0.1579	0.1571	0.0342	-0.0252
8	Lampung	0.0579	0.0571	0.0342	0.0491
9	Bangka Belitung	-0.4421	-0.4429	-0.3658	0.1491
10	Riau Islands	-0.1421	-0.1429	-0.6658	
11	West Java	0.1579	0.1571	0.0342	0.2491
12	Central Java	-0.0421	-0.0429	-0.0658	-0.0509
13	DI Yogyakarta	-0.0421	-0.0429	-0.0658	-0.1509
14	East Java	-0.0421	0.0571	0.0342	-0.0509
15	Banten	-0.1421	-0.1429	0.0342	
16	Bali	0.0579	0.0571	-0.0658	-0.1509
17	West Nusa Tenggara	0.1579	0.1571	0.0342	-0.0509
18	East Nusa Tenggara	0.1579	0.1571	0.0342	-0.1509
19	West Borneo	0.1579	0.1571	0.0342	
20	Central Borneo	0.1579	0.1571	0.0342	
21	South Borneo	0.0579	0.0571	0.0342	
22	East Borneo	-0.0421	-0.0429	0.0342	
23	North Borneo	-0.3421	-0.3429	-0.4658	
24	North Sulawesi	0.1579	0.1571	0.0342	-0.1509
25	Central Sulawesi	0.0579	0.0571	0.0342	0.0491
26	South Sulawesi	0.1579	0.1571	0.0342	-0.1509
27	South-east Sulawesi	0.1579	0.1571	0.0342	-0.0509
28	Gorontalo	-0.2421	-0.2429	-0.1658	
29	West Sulawesi	0.0579	0.0571	0.0342	
30	Maluku	0.1579	0.1571	0.0342	
31	North Maluku	-0.2421	-0.2429	-0.0658	
32	West Papua	-0.3421	-0.3429	-0.0658	-0.0509
33	Papua	0.1579	0.1571	-0.2658	-0.1509
Indonesia total		0.1579	0.1571	0.0342	-0.1509

Source: Author's own computation (2024).

Note: YSI values are computed according to the algorithm described in the methodology section.

coffee farmers utilizing non-optimal Robusta varieties, which in turn affects their production levels. However, for yields exceeding 400 kg/ha, Robusta species show greater resilience to various production-affecting factors compared to Arabica coffee. Several superior varieties of Robusta coffee have been developed with favorable yield potentials and specific resilience characteristics. Varieties such as SA 237 and BP 288 exhibit

moderate yields, ranging between 0.8–1.7 tons per hectare, and are noted for their tolerance to the coffee berry borer (*Hypothenemus hampei*) and drought conditions, while high-yielding varieties like SA 203, NP 936, BP 534, BP 436, BP 920, and BP 939 demonstrate yields of approximately 1.4–2.1 tons per hectare but are more susceptible to parasitic nematodes (Randriani; Dani, 2018).

Table 2: Average Yields for Total Coffee, Smallholder Coffee, Robusta Coffee, and Arabica Coffee in Indonesia (kg/ha).

No	Provinces	TOTAL	SMALLH	ROB	ARAB
1	Aceh	726	726	547	756
2	North Sumatra	1074	1075	754	1162
3	West Sumatra	876	873	929	827
4	Riau	901	901	901	
5	Jambi	862	863	870	615
6	South Sumatra	736	736	736	
7	Bengkulu	768	768	767	852
8	Lampung	838	838	839	609
9	Bangka Belitung	353	353	353	766
10	Riau Islands	70	70	245	
11	West Java	832	833	799	874
12	Central Java	667	658	685	534
13	DI Yogyakarta	541	541	544	456
14	East Java	734	729	752	772
15	Banten	458	458	458	
16	Bali	572	572	583	542
17	West Nusa Tenggara	598	601	590	616
18	East Nusa Tenggara	529	530	505	596
19	West Borneo	542	542	586	
20	Central Borneo	609	609	609	
21	South Borneo	594	594	594	
22	East Borneo	265	265	265	
23	North Borneo	321	321	321	
24	North Sulawesi	586	586	584	642
25	Central Sulawesi	724	724	728	692
26	South Sulawesi	633	627	568	666
27	South-east Sulawesi	444	444	444	
28	Gorontalo	476	476	476	
29	West Sulawesi	633	633	625	661
30	Maluku	608	608	608	
31	North Maluku	224	224	224	
32	West Papua	412	412	1063	350
33	Papua	519	519	367	532
	Indonesia total	751	750	734	814

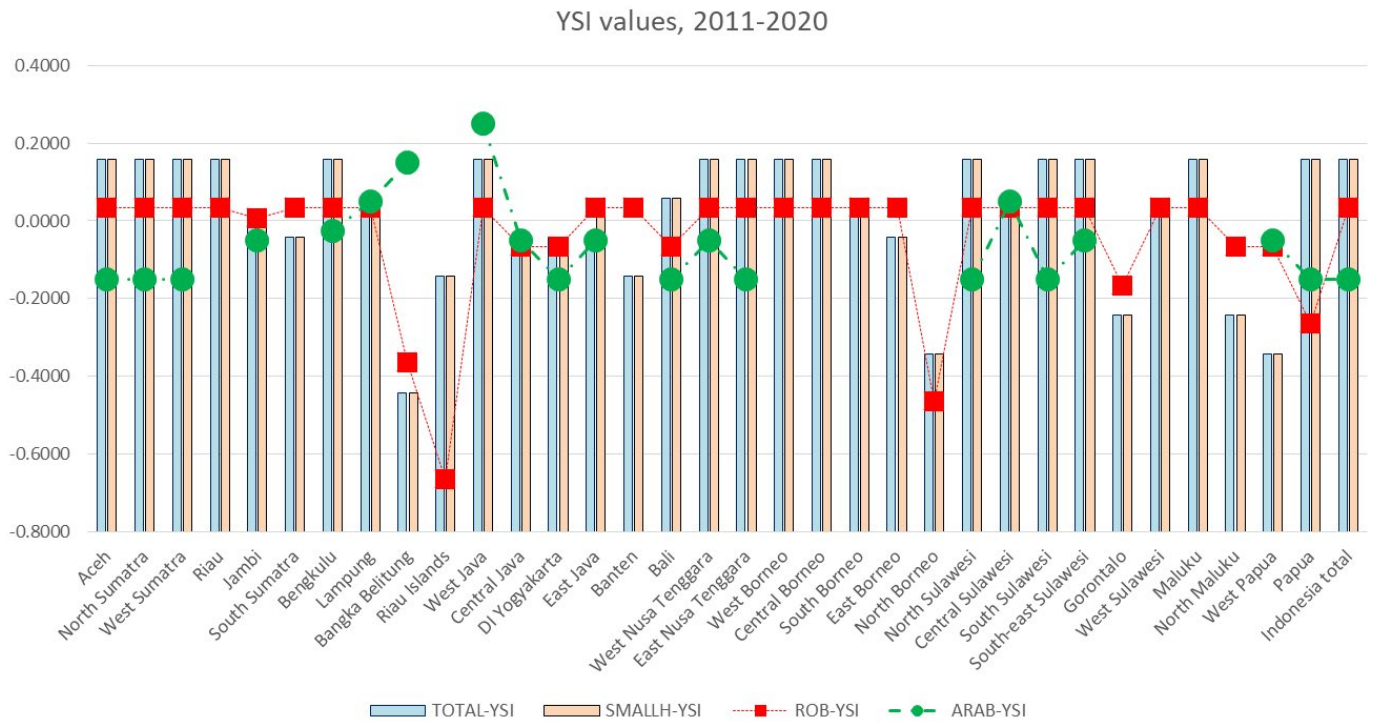


Figure 3: Comparison of YSI Values Across Provinces in Indonesia.

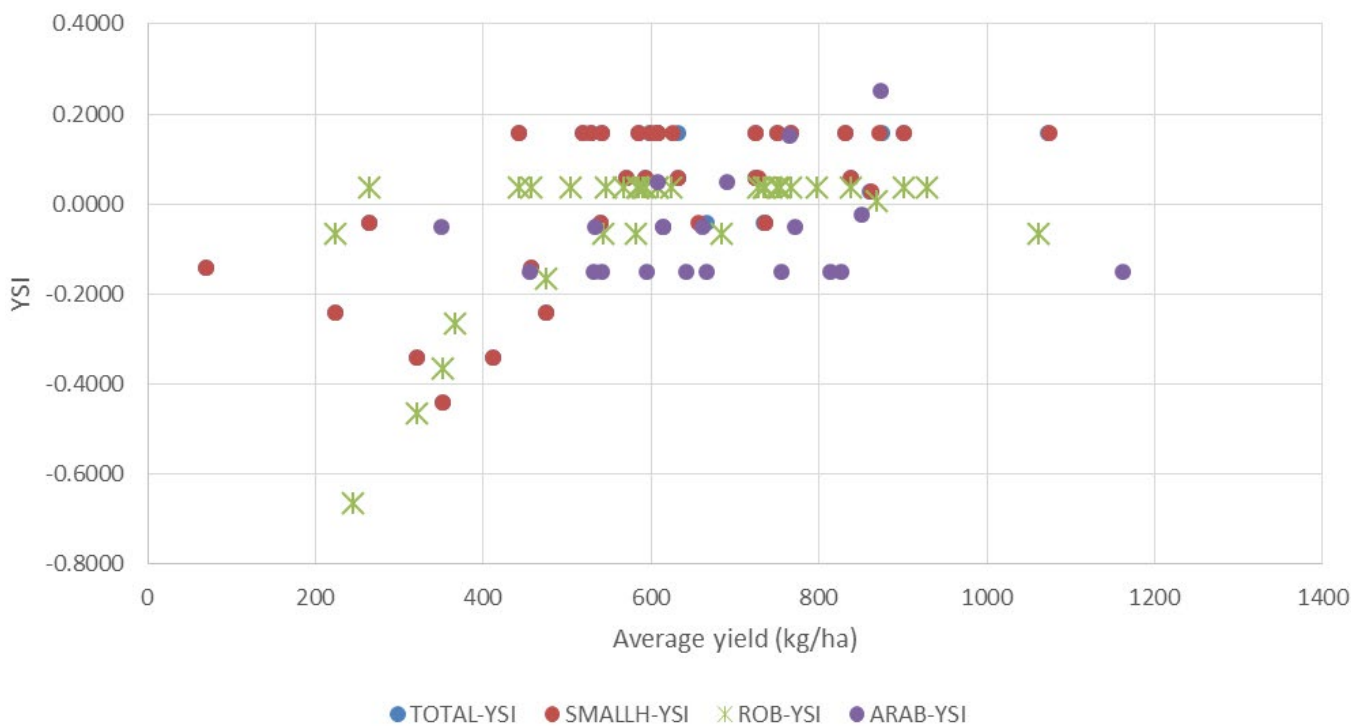


Figure 4: Relationship Between Average Yield (kg/ha) and YSI.

4 DISCUSSION

Coffee is one of the most important crops in Indonesia, and the stability of coffee yields significantly influence the income of coffee growers. The coffee yields are obviously

influenced by soil and climate, as well as farming practices, and several other factors. The concept of YSI is to evaluate, whether the actually applied farming technology is suitable to climate or soil, i.e. whether the crop is farmed in a resilient way, so that changing weather and soil conditions do not

significantly diminish the yield. Climatic factors are the most limiting factor for coffee production, and according to predictions, negative climate impacts dominate in all the main producing regions (Grüter et al., 2022). Climate change poses a significant threat, with rising temperatures potentially reducing suitable cultivation areas for Arabica and Robusta coffee by over 50% by 2050 (Bunn et al., 2015). Furthermore, increased frequency and intensity of extreme weather events can lead to lower yields and greater pest and disease incidence (Bilen et al., 2023; Bracken; Burgess; Girkin, 2023). As climate conditions change, coffee cultivation may shift geographically, potentially encroaching on natural forests, which poses risks to biodiversity and ecosystem services (Magrach; Ghazoul, 2015). Events like El Niño and the Indian Ocean Dipole (IOD) cause significant production anomalies, with La Niña years resulting in yield declines of 6% to 22% across various regions. Positive IOD phases also contribute to yield reductions, ranging from 1% to 15% (Sarvina et al., 2021). Implementing sustainable practices, such as shade planting and improved pest management, can mitigate climate impacts and boost productivity (Ramadhillah; Masjud, 2024).

The coffee yield trends were analysed by Bacsi, Fekete-Farkas and Ma'ruf (2022), comparing the YSI values of 1961-1994 to 1995-2020, for 12 major coffee producer countries, including Indonesia. In this analysis Indonesia was among the four most stable coffee producers according to YSI in the 1961-1994 period, together with Peru, Honduras and Guatemala, with $YSI=0.0424$. In 1995-2020, the country improved considerably its coffee yield stability to 0.0877, being second after Guatemala in the stability ranking. This improving stability trend is in line with our present results, where the last 10 years (2011-2020) showed even better stability values with $YSI=0.1579$. Hollósy, Ma'ruf and Bacsi (2023) also employed the same YSI methodology to analyse the stability of six crops in seven Asian countries, including Indonesia, for the periods 1961-1994 and 1995-2020. According to their results, in the first period rice and bananas were more stable crops than coffee in Indonesia, while in the second period only tea yields showed larger YSI than coffee.

Indonesia's coffee production is predominantly composed of Robusta beans, which are characterized by a bitter flavor profile and higher caffeine content compared to Arabica beans (Sumarjono et al., 2019; Nangameka et al., 2023). Globally, however, the market for Arabica coffee is substantially larger, capturing around 70% of the global coffee trade, while Robusta makes up only 30%. In Indonesia, the production ratio is reversed: Robusta accounts for 80% of the nation's coffee output, while Arabica represents a mere 20% (Harsono; Wibowo; Supriyanto, 2021). This contrast is largely attributed to the distinct growing conditions required by each coffee type. Arabica coffee thrives in specific environments—higher altitudes, cooler climates, and greater rainfall—

whereas Robusta is more resilient and can be cultivated across diverse environmental conditions, including lower elevations (Harsono; Wibowo; Supriyanto, 2021).

Although Robusta dominates Indonesia's coffee sector, Arabica holds a comparative advantage on the global market due to its quality and classification as a specialty coffee (Ashardiono; Trihartono, 2024). Furthermore, the Arabica market is generally more lucrative, while Robusta tends to command lower prices internationally (Kath et al., 2020; Valencia-Lozano et al., 2021; Tampubolon et al., 2023). Nevertheless, seizing this opportunity requires addressing numerous challenges and strategic considerations, particularly for smallholder farmers who often rely on traditional agricultural practices and lack access to advanced technologies.

As our results show, Arabica yield series are rather unstable, while Robusta coffee is characterized with relatively stable yields in most of Indonesia. However, when regions are analysed separately, Robusta is stable in 70% of the regions, while Arabica is stable only in 20% of the producing regions.

The Aceh Province in northern Sumatra is a notable center for Arabica coffee production, particularly for the well-known "Gayo coffee" (Haswidi et al., 2017). Aceh's mountainous topography, with elevations exceeding 1,000 meters above sea level, provides an optimal environment for Arabica cultivation due to its cooler, more stable climate, which helps mitigate pest and disease risks. The region's diverse climate and soil conditions contribute to the distinctive taste profile of Gayo Arabica coffee, a critical factor in its global recognition (Tarigan; Randriani, 2023), with varieties selected for specific attributes such as yield potential, disease resistance, and cup quality (Wardiana et al., 2024). However, all varieties become increasingly vulnerable to diseases when cultivated below 1,000 meters (Hulupi; Nugroho; Yusianto, 2013).

In Central Aceh, a shift is underway to enhance the value of Arabica coffee through product diversification, including roasted coffee, instant coffee, and other derivatives, aiming to strengthen its competitiveness in markets across Europe and the United States (Fadli et al., 2022). Gayo coffee is not only integral to Aceh's economy but also to its cultural identity; however, the region also confronts modernization and cultural shifts (Wulandari et al., 2024). As our results show, the total YSI value for Aceh is among the highest (0.1579) as well as the Robusta stability index (0.0342), but the Arabica production is very unstable (-0.1509), being among the lowest Arabica YSI values.

The same is true for North Sumatra Province, located in the northern part of Sumatra Island. In this province, Arabica coffee production is well-established with notable varieties such as Lintong, Mandheling (Hartatri; Aklimawati; Neilson, 2019), Sidikalang, Samosir, and Simalungun coffee (Haswidi et al., 2017). In contrast to Aceh, coffee yields in North Sumatra are

significantly higher, likely due to the types of coffee varieties cultivated, particularly Sigarar Utang with yield average 1.5 ton/ha (Randriani; Dani, 2018). However, this variety is vulnerable to pest attacks (Kuswardani et al., 2023), though specific Arabica genotypes like P 5 from Dairi District and P 7 from Toba Samosir District have been examined for resistance to coffee leaf rust (Malau; Sihotang, 2023).

In contrast, the southern region of Sumatra is predominantly focused on Robusta coffee production. For example, Lampung Province is known for “Lampung coffee,” while South Sumatra is renowned for “Semendo coffee.” Although the region is largely dedicated to Robusta, there is also Arabica coffee production, such as “Kerinci coffee,” grown in Jambi Province. South Sumatra ranks among Indonesia’s primary coffee-producing areas, with an emphasis on Robusta cultivation. The use of locally adapted, high-yield Robusta varieties has proven beneficial in sustaining productivity amid climatic challenges (Hasibuan et al., 2022). Despite favorable conditions, the average productivity in Indonesia, including Lampung, remains around 600 kg/ha, which is below the potential yield of 1,000 kg/ha, indicating opportunities for productivity improvements (Widiyani; Hartono, 2021). The climate in South Sumatra is generally well-suited for Robusta cultivation, with projections suggesting that much of the region will maintain high suitability for coffee production under various climate scenarios, indicating a stable future for Robusta coffee (Whibowo; Arifianto; Ferdiansyah, 2024). The YSI value for Robusta in South Sumatra is among the highest (0.0342), while the overall YSI for the province is negative (-0.0421), indicating instability.

Bali Province is known for its Arabica coffee varieties, particularly Pupuan and Kintamani coffee (Hartatri; Aklimawati; Neilson, 2019). In contrast, East Nusa Tenggara produces both Robusta, such as Tambura and Wae Rebo coffee, and Arabica varieties like Bajawa and Sokoria coffee (Haswidi et al., 2017). Coffee serves as a significant export commodity for Bali, playing a crucial role in the local economy. However, low productivity levels threaten the sustainability of Balinese Arabica coffee farming, further complicated by socio-economic challenges (Dewi; Sudarma, 2020). However, both Robusta, and Arabica YSI values are negative (-0.0658 and -0.1509, respectively), indicating that coffee production is not very resilient to external stresses in this area.

West Java is recognized for its distinctive Arabica coffee varieties, including Java Preanger, Ciwidey, and Puntang coffee, while Central Java is known for its Arabica Sindoro Sumbing and Robusta Temanggung varieties. In East Java, Arabica coffees like Jampit and Ijen Raung also hold prominence (Haswidi et al., 2017). Since 1907, Java has adopted advanced breeding methods, including selection, cross-pollination, and grafting, leading to significant yield improvements—some areas have recorded yield increases

up to 100% over successive generations. The selection of superior clones, such as disease-resistant varieties, has further contributed to yield optimization (Hulupi; Mawardi; Yusianto, 2012). According to our results West Java is one of the most suitable regions for coffee, both for Robusta and Arabica, with outstanding stability values (YSI=0.0342 for Robusta and YSI=0.2491 for Arabica), and the very positive Arabica value is the highest in Indonesia.

Borneo is recognized for its coffee varieties, particularly Kubu Raya coffee from West Borneo Province and Kota Waringin coffee from Central Borneo (Haswidi et al., 2017). In South Borneo’s Banjar Regency, coffee productivity reaches 520 kg/ha annually, a relatively high yield compared to other areas in the province. Despite this potential, coffee plantation development remains stagnant, indicating the need for strategic interventions. Robusta yields show high stability in West, Central, South and East Borneo (YSI=0.0342), but in North Borneo the same index is negative (-0.4658), making this region one of the most unstable areas of the country.

In Sulawesi, Gorontalo Province is a significant producer of Robusta coffee, particularly Pinogu coffee, while Arabica coffee is predominantly cultivated in South Sulawesi, where varieties such as Toraja, Kalosi Enrekang, and Benteng Alla are highly recognized (Haswidi et al., 2017; Hartatri; Aklimawati; Neilson, 2019). Land suitability, effective plantation management, including precise fertilization, pruning, and pest control, agricultural inputs—urea, Zwavelzure Ammoniak (ZA), herbicides, manure, and labor—are critical to maintaining productivity and sustainability in coffee farming, particularly in Enrekang (Thamrin, 2014). Interestingly, while Robusta produces very stable yields (YSI=0.0342) in the whole Sulawesi province, Arabica yield series are rather unstable with negative YSI, with the exception of Central Sulawesi, which is one of the four regions with positive YSI for Arabica (0.0491).

Papua is a significant region for the production of various Arabica coffee species, such as Nabire, Dogiyai, Cartenz, and Baliem Valley coffees (Haswidi et al., 2017). The mountainous areas, particularly the Arfak Mountains and Dogiyai Regency, situated at altitudes of 800 to 3,000 meters, provide ideal environmental conditions for Arabica coffee cultivation, supporting not only high-quality yield but also potential agritourism development. However, the full potential of Papua’s coffee sector is constrained by infrastructure limitations and insufficient farmer empowerment initiatives. In spite of good quality yields, the yield stability index values are negative for both Arabica and Robusta, which may be due to the mentioned limiting factors. Enhancing the region’s coffee production requires strategic focus on technical skill development, optimized land use, and strengthening of farmer institutions to ensure sustainable agricultural growth (Bogaa et al., 2024).

The comparison of yield stability for smallholders to that of the total yield stability indicates that smallholder yields are somewhat less stable than total yield stability, in every region, with the only exception of East Java, where total YSI is negative, while smallholder YSI is positive. This circumstances indicates that smallholders have generally less access to more resilient technologies, and their reliance on traditional farming practices may be more vulnerable to environmental changes than more modern farming practices used by larger businesses.

Our analysis showed, that higher average yields are positively related to yield stability in Indonesian coffee production, The correlation coefficients between average yields and yield stability index values showed large positive values (0.533–0.616) for total coffee production, and for smallholder coffee production, as well as for Robusta species, and a small positive value for Arabica. This is in contrast with previous research findings by Khalili and Pour-Aboughadareh (2016) and Nielsen and Vigil (2018), that found a negative relationship between yield levels and yield stability. Our results show, that coffee production in Indonesia does not follow this trend, and higher yields can be maintained with better yield stability, i.e. currently applied production technologies are efficient and reliable at the same time.

5 CONCLUSIONS

This study assessed Indonesian coffee yield stability using a YSI index focusing on significant fluctuations. Results revealed substantial regional variations, indicating current production methods aren't equally effective across different environments. Smallholder farms showed lower efficiency and resilience compared to larger operations. Robusta demonstrated greater stability than Arabica, which maintained consistent yields in only 20% of regions. These findings highlight the need for location-specific approaches and underscore Robusta's better adaptation to most Indonesian growing conditions compared to more sensitive Arabica varieties.

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7 AUTHORS' CONTRIBUTION

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8 REFERENCES

- ACOSTA-ALBA, I. et al. Integrating diversity of smallholder coffee cropping systems in environmental analysis. **International Journal of Life Cycle Assessment**, 25(2):252-266, 2020.
- ASHARDIONO, F.; TRIHARTONO, A. Optimizing the potential of Indonesian coffee: A dual market approach. **Cogent Social Sciences**, 10(1), 2024.
- ASSEFA, Y. et al. Crop diversification in rice-based systems in the polders of Bangladesh: Yield stability, profitability, and associated risk. **Agricultural Systems**, 187:102986, 2021.
- BACSI, Z.; FEKETE-FARKAS, M.; MA'RUF, M. I. Coffee Yield Stability as a Factor of Food Security. **Foods**, 11(19):3036, 2022.
- BACSI, Z.; HOLLÓSY, Z. A yield stability index and its application for crop production. **Analecta Technica Szegedinensia**, 13(1):11-20, 2019a.
- BACSI, Z.; HOLLÓSY, Z. The yield stability index reloaded - The assessment of the stability of crop production technology. **Agriculturae Conspectus Scientificus**, 84(4):319-331, 2019b.
- BACSI, Z.; VIZVÁRI, B. Technological development and the stability of technology in crop production. **Journal of Central European Agriculture**, 3(1):63-72, 2002.
- BICHO, N. C. et al. Identification of nutritional descriptors of roasting intensity in beverages of Arabica and Robusta coffee beans. **International Journal of Food Sciences and Nutrition**, 62(8):865-871, 2011.
- BILEN, C. et al. A systematic review on the impacts of climate change on coffee agrosystems. **Plants**, 12(1):1-20, 2023.
- BOGAA, I. et al. Empowerment model for coffee farmers in dogiyai regency, papua: Effective strategies for capacity building. **International Journal of Social Science and Human Research**, 7(6):3956-3961, 2024.
- BORRELLA, I.; MATAIX, C.; CARRASCO-GALLEGO, R. Smallholder farmers in the speciality coffee industry: opportunities, constraints and the businesses that are making it possible. **IDS Bulletin**, 46(3):29-44, 2015.

- BRACHO-MUJICA, G.; HAYMAN, P. T.; OSTENDORF, B. Modelling long-term risk profiles of wheat grain yield with limited climate data. **Agricultural Systems**, 17:393-402, 2019.
- BRACKEN, P.; BURGESS, P. J.; GIRKIN, N. T. Opportunities for enhancing the climate resilience of coffee production through improved crop, soil and water management. **Agroecology and Sustainable Food Systems**, 47(8):1125-1157, 2023.
- BUNN, C. et al. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. **Climatic Change**, 129(1-2):89-101, 2015.
- CAMPERA, M. et al. Does the presence of shade trees and distance to the forest affect detection rates of terrestrial vertebrates in coffee home gardens? **Sustainability**, 13(15):8540, 2021.
- CANDELO, E. et al. Turning farmers into business partners through value co-creation projects. Insights from the coffee supply chain. **Sustainability**, 10(4):15-17, 2018.
- CUDDY, J. D. A.; VALLE, P. A. DELLA. Measuring the instability of time series data. **Oxford Bulletin of Economics and Statistics**, 40(1):79-85, 1978.
- DE ALMEIDA, D. et al. Marker-assisted pyramiding of multiple disease resistance genes in coffee genotypes (*Coffea arabica*). **Agronomy**, 11(9):1-18, 2021.
- DEVKOTA, M. et al. Increasing profitability, yields and yield stability through sustainable crop establishment practices in the rice-wheat systems of Nepal. **Agricultural Systems**, 173:414-423, 2019.
- DEWI, I. A. L.; SUDARMA, I. M. Faktor-faktor pendukung keberlanjutan usahatani kopi arabika di provinsi bali. **SOCA: Jurnal Sosial, Ekonomi Pertanian**, 14(1):158, 2020.
- DIRO, S.; TESFAYE, A.; ERKO, B. Determinants of adoption of climate-smart agricultural technologies and practices in the coffee-based farming system of Ethiopia. **Agriculture and Food Security**, 11(1):1-14, 2022.
- DUFFY, C. et al. Agroforestry contributions to smallholder farmer food security in Indonesia. **Agroforestry Systems**, 95(6):1109-1124, 2021.
- FADLI. et al. Arabica coffee processed product development strategy in central aceh district. **International Journal of Economic, Business, Accounting, Agriculture Management and Sharia Administration (IJEBA)**, 2(6):1300-1314, 2022.
- GRÜTER, R. et al. Expected global suitability of coffee, cashew and avocado due to climate change. **PLoS ONE**, 17(1):1-24, 2022.
- HARSONO, S. S.; WIBOWO, R. K. K.; SUPRIYANTO, E. Energy balance and green house gas emission on smallholder java coffee production at slopes ijen raung plateau of Indonesia. **Journal of Ecological Engineering**, 22(7):271-283, 2021.
- HARTATRI, D. F. S.; AKLIMAWATI, L.; NEILSON, J. Analysis of specialty coffee business performances: Focus on management of farmer organizations in Indonesia. **Pelita Perkebunan**, 35(2):140-155, 2019.
- HASIBUAN, A. M. et al. Local-adapted and high-yield varieties for sustainable Robusta coffee farming: Evidence from South Sumatera, Indonesia. **IOP Conference Series: Earth and Environmental Science**, 974:012130, 2022.
- HASWIDI, A. et al. **Indonesian Coffee Craft & Culture**. Jakarta, Indonesia: BEKRAF: Afterhours Books. 2017. 255p.
- HIDAYAT, E. et al. Land suitability evaluation of arabica coffee (*Coffea Arabica* L) plantation in Subdistrict Aie Dingin, Lembah Gumanti, Indonesia. **IOP Conference Series: Earth and Environmental Science**, 583:012005, 2020.
- HOLLÓSY, Z.; MA'RUF, M. I.; BACSI, Z. Technological advancements and the Changing face of crop yield stability in Asia. **Economics**, 11(12):1-24, 2023.
- HOWARTH, C. J. et al. Genotype and environment affect the grain quality and yield of winter oats (*Avena sativa* L.). **Foods**, 10(10):2356, 2021.
- HULUPI, R.; MAWARDI, S.; YUSIANTO, Y. Pengujian sifat unggul beberapa klon harapan kopi arabika di kebun percobaan Andungsari, Jawa Timur (Testing for superior traits of some arabica coffee promising clones at Andungsari research station, East Java). **Pelita Perkebunan**, 28(2):62-71, 2012.
- HULUPI, R.; NUGROHO, D.; Y. Performance of some arabica coffee local varieties from gayo highland. **Pelita Perkebunan**, 29(2):69-81, 2013.
- KAMIDI, R. E. Relative stability, performance, and superiority of crop genotypes across environments. **Journal of Agricultural, Biological, and Environmental Statistics**, 6(4):449-460, 2001.
- KATH, J. et al. Not so robust: Robusta coffee production is highly sensitive to temperature. **Global Change Biology**, 26(6):3677-3688, 2020.

- KHALILI, M.; POUR-ABOUGHADAREH, A. Parametric and non-parametric measures for evaluating yield stability and adaptability in barley doubled haploid lines. **Journal of Agricultural Science and Technology**, 18(3):789-803, 2016.
- KUSWARDANI, R. A. et al. Influence of monoculture and polyculture planting patterns on the intensity of pest attacks by *Helopeltis* sp. on arabica coffee of the sigarang utang variety in north tapanuli regency. **Jurnal Penelitian Pendidikan IPA**, 9(12):11296-11301, 2023.
- LAKSONO, P. et al. Farmers' willingness to adopt geographical indication practice in Indonesia: A psycho behavioral analysis. **Heliyon**, 8(8):e10178, 2022.
- MADEMBO, C.; MHLANGA, B.; THIERFELDER, C. Productivity or stability? Exploring maize-legume intercropping strategies for smallholder Conservation Agriculture farmers in Zimbabwe. **Agricultural Systems**, 185:102921, 2020.
- MAGRACH, A.; GHAZOUL, J. Climate and pest-driven geographic shifts in global coffee production: Implications for forest cover, biodiversity and carbon storage. **PLoS ONE**, 10(7):1-15, 2015.
- MALAU, S.; SIHOTANG, M. R. Components of genetic of coffee leaf rust symptoms in genotypes of Arabica coffee (*Coffea arabica* L.). **IOP Conference Series: Earth and Environmental Science**, 1241:012006, 2023.
- MARSILANI, O. N.; WAGIMAN; SUKARTIKO, A. C. Chemical profiling of western Indonesian single origin robusta coffee. **IOP Conference Series: Earth and Environmental Science**, 425:012041, 2020.
- NANGAMEKA, Y. et al. Is arabica coffee farming financially feasible? **International Journal of Science, Technology & Management**, 4(3):681-687, 2023.
- NIELSEN, D. C.; VIGIL, M. F. Wheat yield and yield stability of eight dryland crop rotations. **Agronomy Journal**, 110(2):594-601, 2018.
- OKIM, F.; HANANI, N.; SYAFRIAL, S. The impact of input and output prices on indonesian coffee production and trade performance. **Habitat**, 33(1):33-43, 2022.
- PIEPHO, H. P. Methods for comparing the yield stability of cropping systems - A review. **Journal of Agronomy and Crop Science**, 180(4):193-213, 1998.
- PRIVAT, I. et al. Differential regulation of grain sucrose accumulation and metabolism in *Coffea arabica* (Arabica) and *Coffea canephora* (Robusta) revealed through gene expression and enzyme activity analysis. **New Phytologist**, 178(4):781-797, 2008.
- PUTRA, A. I.; BUDISUSANTO, Y.; DEVIANTARI, U. W. Metode spasial temporal. **Studi Kasus: Seluruh Indonesia**, 20(2):71-84, 2022.
- RAHMAWATI, F.; CHUMAIDIYAH, E. Business design and risk analysis of sonja coffee shop with the concept of coworking space. **IOP Conference Series: Materials Science and Engineering**, 1003:012039, 2020.
- RAMADHILLAH, B.; MASJUD, Y. I. Climate change impacts on coffee production in Indonesia: A review. **Journal of Critical Ecology**, 1(1):1-7, 2024.
- RANDRIANI, E.; DANI. **Pengenalan varietas unggul kopi**. Jakarta, Indonesia: IAARD Press, 2018.
- ROSIANA, N.; FERYANTO. Farmer sales decisions and the sustainability of the coffee supply chain in Indonesia. **IOP Conference Series: Earth and Environmental Science**, 1107:012083 2022.
- ROSYIHUDDIN, M.; SUDARMIATIN, S.; BIDHIN, R. Internationalization strategy for sembalun specialty coffee to meet foreign consumer demand; case study of kopikey SMEs, Lombok, Indonesia. **East Asian Journal of Multidisciplinary Research**, 3(4):1611-1620, 2024.
- SARVINA, Y. et al. The impacts of climate variability on coffee yield in five indonesian coffee production centers. **Coffee Science**, 16: e161917, 2021.
- ŠEREMET, D. et al. Antioxidant and sensory assessment of innovative coffee blends of reduced caffeine content. **Molecules**, 27(2):1-18, 2022.
- SETYONINGTYAS, Y. D.; DARMAWATI, E.; SUTRISNO. Optimized utilization of post-harvest coffee agricultural equipment and machines. **IOP Conference Series: Earth and Environmental Science**, 1038:012070, 2022.
- SHIMALES, T. et al. Management intensity affects insect pests and natural pest control on Arabica coffee in its native range. **Journal of Applied Ecology**, 60(5):911-922, 2023.
- SOTT, M. K. et al. Precision Techniques and Agriculture 4.0 technologies to promote sustainability in the coffee sector: state of the art, challenges and future trends. **IEEE Access**, 8:149854-149867, 2020.
- SUMARJONO. et al. The dynamics of social culture of the smallholder coffee farmers in Mulyorejo village, Silo district, Jember Regency, 2000-2017. **IOP Conference Series: Earth and Environmental Science**, 243:012166, 2019.

- SUMMASE, I. et al. Development strategy of coffee agribusiness. **IOP Conference Series: Earth and Environmental Science**, 486:012025, 2020.
- TARIGAN, E. B.; TAMPUBOLON, J. et al. Indonesian coffee development path: production and international trade. **Asian Journal of Agricultural Extension, Economics & Sociology**, 41(12):316-328, 2023.
- TARIGAN, E. B.; RANDRIANI, E. Cupping test of some varieties of Gayo arabica coffee at different altitudes in Central Aceh District. **IOP Conference Series: Earth and Environmental Science**, 1133:012002, 2023.
- TAVARES, S. et al. Identification of HIR, EDS1 and PAD4 genes reveals differences between coffea species that may impact disease resistance. **Agronomy**, 13(4):1-26, 2023.
- TENRIAWARU, A. N. et al. Coffee agribusiness and income farmers. **IOP Conference Series: Earth and Environmental Science**, 486:1, 2020.
- THAMRIN, S. Faktor-faktor yang mempengaruhi produksi usahatani kopi arabika di kabupaten enrekang sulawesi selatan factors affecting the production of arabica coffee farming at enrenkang south sulawesi. **Jurnal AGRIC**, 26(1):1-6, 2014.
- VALENCIA-LOZANO, E. et al. *Coffea arabica* L. resistant to coffee berry borer (*Hypothenemus hampei*) Mediated by Expression of the *Bacillus thuringiensis* Cry10Aa Protein. **Frontiers in Plant Science**, 12:765292, 2021.
- VEGA, F. E. et al. Early growth phase and caffeine content response to recent and projected increases in atmospheric carbon dioxide in coffee (*Coffea arabica* and *C. canephora*). **Scientific Reports**, 10:5875, 2020.
- VIONITA, S.; KARDHINATA, E. H.; DAMANIK, R. I. Morphology identification and description of coffee plants (*Coffea* sp) in Karo District. **IOP Conference Series: Earth and Environmental Science**, 782:042051, 2021.
- VIZVÁRI, B.; BACSI, Z. Módszer a termésátlagok ingadozásának elemzésére. [A method to analyse yield fluctuations – in Hungarian]. **Gazdálkodás**, 46(3):63-74, 2002.
- VOGEL, C. et al. The effects of crop type, landscape composition and agroecological practices on biodiversity and ecosystem services in tropical smallholder farms. **Journal of Applied Ecology**, 60(5):859-874, 2023.
- WARDIANA, E. et al. Yield performance and stability analysis of three cultivars of Gayo Arabica coffee across six different environments. **Open Agriculture**, 9:20220249, 2024.
- WHIBOWO, G. H.; ARIFianto, F.; FERDIANSYAH, E. Climate suitability analysis of robusta coffee and its projections in South Sumatera Province. **Journal of Agricultural Engineering**, 13(2):512, 2024.
- WIDIYANI, D. P.; HARTONO, J. S. S. Studi eksplorasi agroklimat tanaman kopi robusta (*Coffea canephora*) Kabupaten Tanggamus, Lampung. **Jurnal Agrinika: Jurnal Agroteknologi dan Agribisnis**, 5(1):20-29 2021.
- WULANDARI, E. et al. Mountainous Socio-economic and geographical factors in recent aceh gayo vernacular architecture. **IOP Conference Series: Earth and Environmental Science**, 1361:012048, 2024.
- XIANG, W. et al. Estimation of crop yield distribution: implication for crop engineering risk. **Systems Engineering Procedia**, 3:132-138, 2012.
- ZEWDIE, B. et al. Genetic composition and diversity of Arabica coffee in the crop's centre of origin and its impact on four major fungal diseases. **Molecular Ecology**, 32(10):2484-2503, 2023.