

Total phenolic content and antioxidant activity of selected Philippine mulberry fruit genotypes

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ABSTRACT

Recent advancements in mulberry breeding have focused on developing varieties for commercial fruit production, yet information on genotypes grown in the Philippines remains limited. This study evaluated the Total Phenolic Content (TPC) and antioxidant potential of five Philippine mulberry fruit genotypes (Alf-004, Alf-025, Alf-023, Alf-058, and Alfonso). The antioxidant activity was assessed using the DPPH radical scavenging assay, and TPC was determined via the Folin-Ciocalteu method. Results showed that Alf-025 emerged as the most promising variety, exhibiting the highest TPC at 7942.35 mg GAE/L and a superior antioxidant activity of 60.15%. This potency was further validated by Alf-025 having the lowest IC₅₀ where lower concentration of the mulberry variety was needed to inhibit 50% of the free radicals and the highest Trolox Equivalent Antioxidant Capacity (TEAC), which measured antioxidant strength relative to trolox standard where higher TEAC value means higher antioxidant activity. Across all genotypes, antioxidant activity increased in a dose-dependent manner. While Alf-058 recorded the lowest phenolic levels, varieties Alf-004, Alfonso, and Alf-023 showed no significant difference in TPC from one another. These findings establish baseline data for the selected Philippine mulberry fruits and highlight the potential of Alf-025 for use in functional foods and nutraceuticals.

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1. INTRODUCTION

Mulberry is a multipurpose tree and has a huge potential economic value other than sericulture owing to its several unique and special features. Apart from being the sole food plant of the silkworm (*Bombyx mori*), mulberry can be utilized for catering to diversified needs such as food, fodder, fuel, and fiber. Mulberries are of the genus *Morus* belonging to the Moraceae family and a deciduous tree that is grown in various temperate areas of the world. Mulberries are highly appreciated for their sweet fruit with a unique flavor and abundant composition of nutrients, juicy and refreshing. Consumption of ripe fruits could either be fresh or after extraction of juice according to Jalikop et al. (2011) as cited by Hare Krishna (2018).

Previous research reports have demonstrated the presence of bioactive compounds in mulberry fruits (Jiang & Nie, 2015; Gundogdu et al., 2017; Mahmood et al., 2017) which has earned its "Superfood" status, especially, in European countries where it is mainly grown for its fruits (Natic et al., 2015), as cited by Krishna (2018). These large amounts of bioactive compounds in mulberry fruits, including phenolics, and anthocyanins are beneficial to human health with its anti-inflammatory and antioxidant properties.

Some studies now focus on the bioactive components of mulberry. According to Ercisli and Orhan (2007), as cited by Sivakumar et al. (2015), the presence of active ingredients with notable therapeutic functions is attributed to medicinal worthiness. The medicinal and therapeutic effects of mulberry fruits are attributed to the rich content of bioactive ingredients, such as flavonoids, anthocyanins, phenolic acid and other phytochemicals, underscoring their extensive health benefits. With their strong antioxidant properties, these compounds present in mulberry fruits scavenge free radicals and reduce oxidative stress, thereby helping protect cells from damage associated with aging and chronic diseases. Mulberries are a good source of vitamins, minerals, and high amount of anthocyanin. It has been found that mulberry fruit extract has an anti-oxidative property (Tsai et al., 2005).

Berries have gained immense importance for their value in the diet vis-à-vis human health as they are rich sources of a wide variety of antioxidants according to Skrovankova et al., (2015), as cited by Hare Krishna (2018). Studies revealed that the mulberry fruits contain not only an appreciable amount of proteins, carbohydrates, fats, fibers, minerals, and some vitamins but also many bioactive

components, such as anthocyanin, flavonoids, alkaloids, etc. (Onose et al., 2013). Antioxidants are substances that delays, prevent, or remove oxidative damage to a target molecule. It is an inhibitor of the process of oxidation, even at relatively small concentrations, and thus has diverse physiological roles in the body. It acts as scavenger and helps in converting the radicals to less reactive species (Yadav, 2016). Phenolics possess a wide spectrum of biochemical activities such as antioxidant, antimutagenic, and anticarcinogenic properties, as well as the ability to modify gene expression. Phenolic compounds are commonly found in both edible and non-edible herbs, cereals, fruits, vegetables, oils, spices, and other plant materials (Khan et al., 2013).

Nowadays, mulberry fruit is widely consumed both in fresh form and as processed products such as mulberry jam, jelly, wine, and juice drinks in Sericultural countries such as China, Korea, Japan, etc. (Jiang et al., 2013). Mulberry fruit product consumption has been rapidly increasing because of their taste, nutritional value, and biological benefits (Aramwit et al., 2010), as cited by Sivakumar et al. (2015). Moreover, Koyuncu et al. (2024) studied the nutritional and phytochemical composition of mulberry, especially fruit, showing high levels of total phenols, flavonoids, anthocyanins, and ascorbic acid in mulberry fruit compared with other plant parts. It highlights that these compounds are known for their antioxidant activity, which underlies many of the biological benefits attributed to mulberry consumption. Sutthanut et al. (2025) also conducted a clinical trial that evaluated a concentrated mulberry drink rich in phenolic compounds and anthocyanins in obese adults and found meaningful effects on metabolic and cardiovascular risk markers. Therefore, finding new promising sources of natural antioxidants for functional foods or nutraceuticals and the assessment of such properties remains an interesting and useful task.

There are some studies about the physical and chemical properties of fruits of different species but little information is reported on the total phenolic content and antioxidant activity of mulberry. Moreover, limited research studies have been conducted on the antioxidant properties, particularly of the TPC, of mulberry fruiting varieties that were evolved and grown in the Philippines. Previous studies have demonstrated that the antioxidant potential and total phenolic content (TPC) of mulberry fruits are strongly influenced by geographical origin, environmental conditions, and genotype. For instance, Zhang et al. (2024) reported significant differences in phenolic and flavonoid contents of mulberry leaves collected from various regions in China, highlighting the influence of local growing environments on metabolite accumulation. Similarly, Liu et al. (2023) observed that the antioxidant activity and chemical composition of mulberry

fruits cultivated in semi-arid areas varied widely among genotypes, indicating strong genotype–environment interactions. Other comparative studies further confirmed that regional factors such as soil type, temperature, and altitude affect the phenolic profiles and antioxidant capacities of mulberries (*Morus alba* and *M. nigra*) (Hussain et al., 2017; Kim et al., 2021).

Recognizing the untapped potential of local cultivars, this research evaluates the antioxidant properties and phenolic composition of mulberry genotypes grown under Philippine conditions. By assessing the total phenolic content and antioxidant activity of locally cultivated and newly-evolved fruit-bearing mulberry genotypes of DMMMSU-SRDI such as the Alf-025, Alf-004, Alf-023, Alf-058, and Alfonso (NSIC Mb 01), this study establishes essential baseline data to determine their nutraceutical potential. It is hypothesized that these varieties will exhibit significant genotypic variations in their bioactive profiles, and this study aims to quantify these differences to identify the most promising genotypes for sustainable sericulture and the advancement of functional food development.

2. MATERIALS AND METHODS

In this study, five (5) mulberry varieties viz., Alf-004, Alf-025, Alf-023, Alf-058 and Alfonso were used and conducted on mulberry plantations grown and cultivated at the Sericulture Research and Development Institute (SRDI) plantation. These varieties have been previously characterized for their biochemical composition under local conditions, as reported in published literature. The varieties exhibit variability in fruit biochemical attributes, including mineral composition and antioxidant-related constituents, with differences observed among genotypes and across harvesting seasons. Such documented genotypic variation supports their suitability for comparative evaluation of total phenolic content and antioxidant activity (Damasco et al., 2023).

Mulberry fruits transition from pink to red and finally to a dark purple or black color upon reaching full maturity. For this study, ripe fruits of uniform age and ripeness were harvested during the peak abundance months of March and April (dry season). The samples were obtained from 8-year-old mulberry trees grown under conventional cultivation conditions at the DMMMSU-SRDI plantation. To ensure a representative sample of each genotype, 32 trees per variety were sampled, replicated three times.

Good-quality, fresh fruits were manually harvested specifically selecting the mature (colored black) stage at each harvest with fruit sizes ranging from 1–2 cm in length. The harvested fruits were sorted and washed under running tap

water to remove debris, then drained thoroughly. For each variety, the harvested fruits from the 96 trees were pooled to create a composite sample, ensuring a uniform representation of the genotype's biochemical profile. From this pooled stock, three independent replicates of 250 grams each were packed in plastic bags and stored below 4°C until further use.

2.1. Preparation of the mulberry extract

Two hundred (200) grams each of mulberry fruit variety were weighed and placed in a 500-ml beaker. The extraction process involved macerating the fruit in 200 mL of 80% ethanol using a hand blender, after which the mixture was covered and allowed to stand overnight at 4°C. The samples were filtered through a nylon cloth to separate the liquid extract from the solid residue. To ensure maximum recovery of phenolic compounds, the residue was washed twice with an additional 200 mL of ethanol solution.

The resulting filtrate was placed in a rotary evaporator to remove the solvent until a volume of 200 mL remained. This concentrated extract was then weighed and quantitatively transferred into a 1-L volumetric flask, where it was diluted to volume with deionized water to reach a final standardized extract for analysis.

2.2. Determination of antioxidant activity by DPPH radical scavenging assay

The antioxidant capacity of the mulberry samples was determined using the 2,2-diphenyl-1-picrylhydrazil (DPPH) radical scavenging assay based on the method described by Xiao et al. (2020) with slight modifications.

In a testing tube, 5 ml of DPPH solution and 4 mL of Tris-HCl buffer (pH 7.4) were added. Then 1 mL of extract sample was added and mixed immediately for 10 s using a vortex mixer. The mixture was kept in the dark at room temperature for 30 minutes. After which, its absorbance (Abs_s) was measured using UV-vis spectrophotometer (Shimadzu UV-1780, Kyoto, Japan) at 517 nm. A solution of 6 mL of ethanol and 4 mL of Tris-HCl buffer was used as the blank. On the other hand, a solution of 5 mL of DPPH solution + 4 mL Tris-HCl Buffer + 1 mL ethanol was used as the control (Abs_c). This was replicated three times per sample. All reagents were purchased from a local chemical supplier, Speed Laboratories, Pangasinan, Philippines.

The antioxidant activity represented as % radical scavenging activity (%RSA) was calculated using the equation:

$$\% \text{ RSA} = \frac{\text{Abs}_c - \text{Abs}_s}{\text{Abs}_c} \times 100\%$$

where Abs_c is the absorbance of the control, and Abs_s is the absorbance of the sample.

2.2.1. Calculation of IC₅₀

To determine the half-maximal inhibitory concentration (IC₅₀), which represents the concentration of mulberry extract required to neutralize 50% of DPPH radicals, a linear interpolation method was employed ($y = ax + b$). The percentage of Radical Scavenging Activity (%RSA) was plotted as the dependent variable (y) against the varying sample concentrations (x). The IC₅₀ was calculated using the equation:

$$\text{IC}_{50}, \text{mg/mL} (x) = \frac{(y - b)}{a}$$

where x is the IC₅₀ of the sample, y is the inhibition ratio with a value of 50, a is the slope of the line and b is the y-intercept (%RSA).

2.2.2. Calculation of Trolox equivalent antioxidant capacity

The DPPH radical scavenging activity of sample was expressed as Trolox equivalent antioxidant capacity (TEAC). TEAC was calculated as follows:

$$\text{TEAC} = \frac{\text{IC}_{50} \text{ of Trolox } (\mu\text{g/ml})}{\text{IC}_{50} \text{ of extract sample } (\mu\text{g/ml})}$$

The higher TEAC value means the higher DPPH radical scavenging activity. The values of IC₅₀ of extract samples and Trolox were measured on the same day.

2.3. Determination of total phenolic content of mulberry fruits

The total phenolic content (TPC) of the extracts from the different mulberry varieties was determined using the Folin-Ciocalteu assay as described by Lawag et al. (2023) with slight modification. The Folin-Ciocalteu (FC) reagent was prepared by mixing one (1) ml of FC phenol solution with 30 ml deionized water. The foundational method for the Folin-Ciocalteu assay by Singleton & Rossi (1965) and Singleton et al. (1999) was employed.

From each standard gallic acid solution, sample, or blank, 1 ml was pipetted out into a test tube and added with 5 ml of the FC reagent and was mixed thoroughly using a vortex mixer. The mixture was stood for 5 minutes at room temperature and then added with 4 ml of 0.75% sodium carbonate solution. The mixture was incubated for 2 hours at a dark room with temperature before absorbance at 760 nm using a UV-Vis spectrophotometer (Shimadzu UV-1780, Kyoto, Japan). This was replicated three times per sample.

The TPC was expressed as milligram gallic acid equivalent per L sample,

$$GAE \text{ (mg/L)} = \frac{C \times V \times DF}{V_L}$$

where GAE = Gallic acid equivalent (mg/L)
C = Concentration of Gallic Acid (mg/mL)
V = Volume of extract (mL)
DF = Dilution factor
V_L = Volume of extract (L)²³

2.4. Statistical Analysis

Experimental data were computed and statistically analyzed using analysis of variance (ANOVA) using SPSS version 21.0 under a completely randomized design (CRD). Prior to ANOVA, data normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. Mean comparisons among treatments were performed using Tukey's Honest Significant Difference (HSD) test at the 5% level of significance ($p < 0.05$).

3. RESULTS AND DISCUSSION

3.1 Antioxidant activity

The IC₅₀ values of the different mulberry varieties are presented in Table 1. Lower IC₅₀ values indicate higher antioxidant activity, as a smaller concentration of mulberry extract is required to inhibit 50% of DPPH radicals. The results revealed significant differences among the varieties ($p < 0.05$). Alf-025 exhibited the highest antioxidant activity, with the lowest IC₅₀ value (2.904 ± 0.0047 mg/mL), followed by Alf-004 (3.298 ± 0.0025 mg/mL), Alf-023 (4.373 ± 0.0012 mg/mL), Alfonso (4.598 ± 0.0035 mg/mL), and Alf-058 (6.548 ± 0.0089 mg/mL). The observed variation in antioxidant activity among the mulberry varieties indicates a genotype-dependent effect ($p < 0.05$), suggesting that genetic differences play a significant role in determining antioxidant activity. This finding is consistent with the report of Krishna (2018), who emphasized that antioxidant levels in mulberry are strongly influenced by genetic makeup.

Table 1: IC₅₀ of Mulberry Varieties

Mulberry Variety	Ave IC 50 (mg/ml)
Trolox Standard	1.350 ± 0.00058^a
Alfonso	4.598 ± 0.0035^e
Alf-004	3.298 ± 0.0025^c
Alf-023	4.373 ± 0.0012^d
Alf-025	2.904 ± 0.0047^b
Alf-058	6.548 ± 0.0089^f

Values represent the mean $\pm$ SD of three replicates. In a column, means with a common letter are not significantly different by Tukey's Honest Significant Difference (HSD) at the 5% level of significance.

Previous research has confirmed that mulberry fruits contain abundant bioactive compounds, including flavonoids, anthocyanins, and phenolic acids, which contribute to their antioxidant properties (Jiang & Nie, 2015; Gundogdu et al., 2017; Mahmood et al., 2017). The high scavenging activity of Alf-025, Alf-004, and Alf-023 indicates their potential as functional food sources and supports their designation as “superfoods” due to their rich phytochemical content. The comparatively lower activity observed in Alf-058 may be attributed to either lower phenolic accumulation or environmental factors that may have affected the biosynthesis of secondary metabolites during fruit development.

The antioxidant activity of the mulberry samples is shown in Figure 2. As expected, the scavenging ability of DPPH increased with higher concentrations of mulberry extract, independent of variety. At 1100 μ g/ml, Alf-025 achieved the highest DPPH scavenging rate at 60.146%, followed by Alf-004 (57.9%), Alf-023 (54.47%), Alfonso (53.46%), and Alf-058 (48.61%). This dose-dependent response aligns with the classical understanding of antioxidant behavior in plant extracts, where higher concentrations of phenolic compounds and other antioxidants can effectively neutralize free radicals (Hussain et al., 2017).

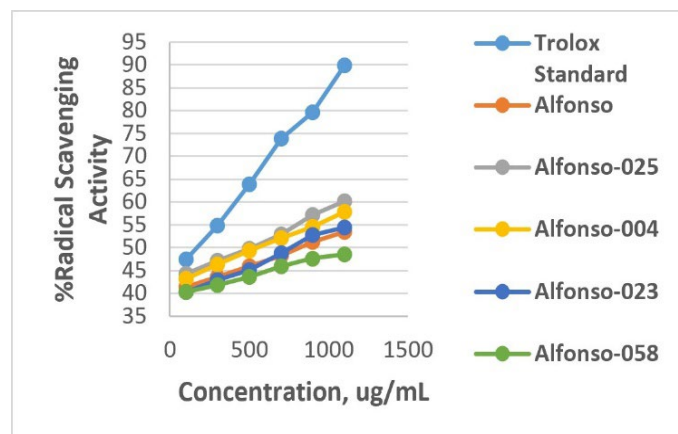


Figure 2: Antioxidant activity of Philippine Mulberry Varieties

The DPPH radical scavenging activity expressed as Trolox Equivalent Antioxidant Capacity (TEAC) further confirmed these findings (Table 2).

Table 2: Trolox equivalent antioxidant capacity of Mulberry Varieties.

Mulberry Variety	TEAC (μ g/ml)
Alfonso	0.2932 ± 0.00025^b
Alf-004	0.4089 ± 0.00036^d
Alf-023	0.3083 ± 0.00006^c
Alf-025	0.4644 ± 0.00074^e
Alf-058	0.2059 ± 0.00026^a

Values represent the mean $\pm$ SD of three replicates. In a column, means with a common letter are not significantly different by Tukey's Honest Significant Difference (HSD) at the 5% level of significance.

Alf-025 again had the highest TEAC (0.46 $\mu\text{g/ml}$), followed by Alf-004 (0.41 $\mu\text{g/ml}$), Alf-023 (0.31 $\mu\text{g/ml}$), Alfonso (0.29 $\mu\text{g/ml}$), and Alf-058 (0.21 $\mu\text{g/ml}$). The TEAC values correlated well with the IC₅₀ and % scavenging results, demonstrating the robustness of the antioxidant measurement and reinforcing the conclusion that Alf-025 exhibits the highest antioxidant capacity among the varieties tested. This correlation between TEAC and IC₅₀ highlights the reliability of using multiple antioxidant assays to comprehensively evaluate bioactivity (Liu et al., 2023).

The observed differences in antioxidant activity among varieties may also be explained by environmental factors, including soil composition, sunlight exposure, rainfall, and temperature. Phenolic compounds, which are the main contributors to antioxidant capacity, are synthesized through the phenylpropanoid pathway in response to both genetic and environmental stimuli (Zhang et al., 2024). Plants growing under higher UV stress or moderate water limitation often accumulate higher levels of phenolics and flavonoids as part of their defense mechanisms (Kim et al., 2021). Therefore, the variations observed among these Philippine-grown genotypes likely reflect both intrinsic genetic potential and environmental influences specific to the cultivation sites.

The superior antioxidant performance of Alf-025 may be attributed primarily to genotype-specific differences in metabolite accumulation. Genetic variability among mulberry varieties is known to influence the synthesis of phenolic compounds through pathways involved in secondary metabolism, thereby affecting overall antioxidant potential. The elevated phenolic content observed in Alf-025 suggests a greater capacity for metabolite production compared with the other varieties evaluated. Additionally, although all samples were cultivated under similar conditions, subtle environmental influences and fruit maturity at harvest may further modulate phytochemical accumulation. Comparable studies on mulberry conducted in other countries have likewise reported significant genotype-dependent variation in antioxidant activity, reinforcing the importance of genetic factors in determining phytochemical composition. Collectively, these findings position Alf-025 as a promising variety with enhanced functional properties.

3.2 Total Phenolic Content (TPC)

The total polyphenol content (TPC) of the mulberry varieties is presented in Table 3. Significant differences in TPC were observed among the varieties ($p < 0.05$). Alf-025 exhibited the highest TPC (7942.35 mg GAE/L), followed by Alf-004 (5878.79 mg GAE/L), Alfonso (5620.65 mg GAE/L), and Alf-023 (4887.73 mg GAE/L), while Alf-058 showed the lowest TPC (1794.24 mg GAE/L). The significantly higher TPC

of Alf-025 ($p < 0.05$) is consistent with its superior antioxidant activity, supporting the well-established association between phenolic content and free radical scavenging capacity (Kong, 2019; Shoib, 2015; Soobrattee, 2005).

Table 3. Total polyphenol content of mulberry varieties.

Mulberry Variety	TPC, mg GAE/L
Alfonso	5620.65 $\pm$ 85.20 ^b
Alf-004	5878.79 $\pm$ 438.97 ^b
Alf-023	4887.73 $\pm$ 684.52 ^b
Alf-025	7942.35 $\pm$ 246.63 ^a
Alf-058	1794.24 $\pm$ 92.86 ^c

Values represent the mean $\pm$ SD of three replicates. In a column, means with a common letter are not significantly different by Tukey's Honest Significant Difference (HSD) at the 5% level of significance

Phenolic compounds possess redox properties that allow them to act as antioxidants, donating hydrogen atoms or electrons to neutralize free radicals. The high TPC in Alf-025 suggests that this variety could be particularly valuable as a functional food ingredient or as part of nutraceutical formulations. These results are consistent with studies in other countries where mulberry genotypes with higher phenolic content demonstrated enhanced antioxidant and antimicrobial activities (Mahmood et al., 2017; Liu et al., 2023).

The differences in TPC observed among varieties may be influenced by several factors such as: (a) genetic variation since certain genotypes have inherently higher enzymatic activity in phenolic biosynthesis pathways; (b) environmental factors where variations in soil nutrients, light intensity, and microclimate conditions can significantly alter secondary metabolite accumulation; and (c) harvest maturity and post-harvest handling wherein phenolic content can fluctuate during fruit ripening, and improper handling can result in degradation of these compounds (Jiang & Nie, 2015).

These findings reinforce the necessity of conducting region-specific evaluations. While global studies have documented the high antioxidant potential of mulberries, this study provides the first detailed assessment of Philippine-grown genotypes, offering baseline data for local cultivation practices.

3.3 Correlation Between TPC and antioxidant activity

Pearson correlation analysis revealed a strong positive correlation ($r = 0.89$) between TPC and antioxidant activity across all varieties. The superior performance of Alf-025 in both TPC (7942.35 mg GAE/L) and antioxidant activity (60.15%) statistically reinforces this link. This suggests that phenolic compounds are major contributors to the antioxidant potential of mulberry fruits. Similar correlations have been reported in other studies, where higher phenolic content consistently predicted stronger antioxidant activity (Zhang et al., 2024; Kim et al., 2021). The high correlation further

validates the use of TPC as a reliable indicator of antioxidant activity in functional food research.

3.4 Implications for sericulture and functional foods

The high antioxidant potential observed in Alf-025 and Alf-004 varieties has practical implications for the sericulture industry in the Philippines. While mulberries are traditionally cultivated for silkworm feed, these findings indicate that certain genotypes could also be leveraged for fruit-based nutraceuticals or functional foods, providing additional income streams for farmers. Breeding programs can prioritize these high-phenolic varieties, promoting dual-purpose cultivation that maximizes both silk production and fruit bioactivity.

Furthermore, the wide variation in TPC and antioxidant activity among genotypes emphasizes the importance of selective cultivation and environmental optimization. By selecting genotypes with proven bioactivity and growing them under conditions favorable for phenolic accumulation, farmers and researchers can improve the nutritional and functional quality of mulberries.

3.5 Comparison with international studies

The results of this study are consistent with previous findings in other countries, though absolute values vary. For example, Liu et al. (2023) reported TPC values ranging from 4000 to 8000 µg GAE/L among Chinese mulberry genotypes, while Kim et al. (2021) observed significant differences in antioxidant activity of fruits grown across diverse Korean regions. These comparisons demonstrate that both genotype and environmental factors contribute to phenolic accumulation and antioxidant capacity, highlighting the importance of localized studies to guide cultivation and utilization strategies.

3.6 Limitations and Future Directions

While this study provides valuable insights into the antioxidant properties of Philippine-grown mulberries, several limitations must be acknowledged. Seasonal variation was not fully captured, which may influence phenolic accumulation. Additionally, only methanolic extracts were evaluated; other solvent systems could reveal additional bioactive compounds. Future research could explore the impact of post-harvest processing, storage, and seasonal variation on antioxidant potential. Furthermore, evaluating silk yield and larval performance in relation to high-antioxidant mulberry genotypes could provide an integrated approach for sericulture optimization.

4. CONCLUSIONS

The findings of this study establish that among the mulberry varieties cultivated at DMMMSU-SRDI, Alf-025 is the most superior genotype in terms of bioactive potential. This variety consistently exhibited the highest total phenolic content and the most potent antioxidant activity, requiring the lowest concentration to neutralize free radicals as evidenced by its IC₅₀ and TEAC values. While Alf-004, Alfonso, and Alf-023 showed comparable phenolic levels, Alf-025 remained significantly distinct, marking it as the premier candidate for further development.

These results hold significant practical relevance for the Philippine agricultural and health sectors, particularly in the advancement of functional foods and nutraceuticals. The high antioxidant potency of Alf-025 and Alf-004 suggests these genotypes are ideal for producing health-optimized products such as juices, jams, and dietary supplements.

Furthermore, these findings support a dual-purpose strategy for the sericulture industry; by prioritizing these high-phenolic varieties in breeding programs, the industry can maximize silk production while simultaneously providing farmers with a secondary, high-value income stream from fruit-based bioactive compounds. To build upon this baseline data, future research should expand toward a wider sampling across different geographical locations to better understand genotype-environment interactions. While this study confirms total phenolic abundance, advanced compound profiling is recommended to identify the specific anthocyanin and flavonoids responsible for the observed bioactivity.

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