

Analysis Of Elevation Effects On The Chemical Composition Of *Moringa Oleifera* Leaves Using A Multivariate Statistical Approach

Marthen Makaborang¹, Nikodemus Paulus Petrus Elisa Nainiti², Marten Luter Lano³, Jemmy Jonson Sula Dethan⁴, and Alfred G.O. Kase⁵

Department of Agricultural Engineering, Faculty of Agricultural Technology,

Universitas Kristen Artha Wacana, Kupang, Indonesia^{1,2,3,4}

Aquatic Resource Management Study Program, Faculty of Fisheries and Marine Science, Universitas Kristen Artha Wacana, Kupang, Indonesia⁵

E-mail Corresponding: marthen89gp@gmail.com

Received: March 30, 2026

Revised: June 2, 2026

Accepted: July 23, 2026

Abstract

This study aimed to compare the chemical composition of *Moringa oleifera* leaves across three elevation-associated sampling ranges and examine relationships among chemical traits. Leaf composition data from samples collected at 0–250, 251–500, and 501–750 m above sea level were evaluated using one-way ANOVA, Duncan's multiple range test, effect size estimation, Pearson correlation, and principal component analysis (PCA). Protein content differed significantly among ranges ($\eta^2 = 0.984$), declining from $31.69 \pm 0.58\%$ in the lowest range to $29.93 \pm 0.28\%$ in the highest. Between these ranges, tannin and crude fiber contents increased from $0.64 \pm 0.21\%$ to $0.86 \pm 0.41\%$ and from $4.91 \pm 0.45\%$ to $7.81 \pm 0.96\%$, respectively. Total phenolic and flavonoid contents showed decreasing trends, from 618.73 ± 69.45 to 486.40 ± 45.78 mg gallic acid equivalents/g and from 2.83 ± 0.11 to 1.51 ± 0.06 mg quercetin equivalents/g, respectively. Protein correlated negatively with tannin, whereas total phenolics correlated positively with flavonoids. The first two principal components explained 93.97% of total variance, separating nutritional traits from structural and defense-related traits. These contrasting patterns are consistent with environmental influences on nutrient accumulation and secondary metabolism. However, site-specific confounding limits attribution to elevation alone. Future studies should incorporate environmental covariates and replicated sampling sites to clarify these relationships.

Keywords: Chemical Composition; Elevation; *Moringa Oleifera*; PCA; Secondary Metabolites.

INTRODUCTION

Moringa oleifera is a tropical plant of considerable strategic value as a food source and reservoir of bioactive compounds, owing to the relatively high levels of protein, phenolic compounds, flavonoids, and dietary fiber in its leaves. In recent years, global interest in moringa leaves has increased markedly for use in functional foods, animal feed, and health-related applications, in line with the growing demand for plant-based nutrients and natural antioxidants (Vergara-Jimenez et al., 2017).

The chemical composition of moringa leaves is strongly influenced by environmental conditions at the growing site. Among these factors, elevation plays a key role, as changes in altitude are closely associated with variations in temperature, radiation intensity, humidity, and soil nutrient availability. Elevation gradients can induce physiological adjustments in plants that directly affect the allocation of primary and secondary metabolism (López-Goldar et al., 2024). Recent studies indicate that differences in elevation are capable of modifying plant nutrient content and secondary metabolites, although the response patterns are highly species-specific and dependent on local environmental conditions.

From a physiological perspective, plant responses to environmental variation are often

explained through the concept of the growth–defense trade-off, which describes a balance in resource allocation between growth-related processes and defense mechanisms. Under relatively favorable conditions, plants tend to prioritize growth and protein synthesis, whereas under more stressful environments, resources are increasingly diverted toward the production of defensive compounds such as tannins and other phenolic substances (Cope et al., 2021). While this concept has been widely validated in modern ecophysiological studies, its application to moringa leaves in dry tropical regions remains limited.

Phenolic compounds and flavonoids represent major groups of secondary metabolites that contribute to antioxidant activity and protection against abiotic stress. Although flavonoids are a subclass of phenolic compounds, these two parameters do not always exhibit identical response patterns to environmental factors, as they are regulated by distinct biosynthetic pathways and metabolic controls (Naikoo et al., 2019). Consequently, the simultaneous assessment of total phenolics and flavonoids is essential for a more comprehensive understanding of the chemical responses of moringa leaves. In addition to primary and secondary metabolites, crude fiber is an important structural component associated with cell wall thickness and the degree of leaf lignification. Several recent studies have reported that fiber content and other structural components of leaves tend to increase under more extreme environmental conditions, including higher elevations, as part of morphological and mechanical adaptation strategies (Onoda et al., 2017; Poorter et al., 2009).

Most previous studies on *Moringa oleifera* leaves have primarily characterized nutritional components or phytochemical profiles under specific cultivation conditions, whereas the extent to which elevation-associated environmental variation is related to the coordinated changes among primary metabolites, secondary metabolites, and structural components remains insufficiently resolved. In particular, empirical evidence is still limited regarding whether elevation gradients are associated with consistent shifts in the balance between growth-related traits (e.g., protein accumulation) and defense or structural traits (e.g., tannins and crude fiber) in *M. oleifera* leaves. Although elevation-related changes in plant chemistry have been investigated in several species using multivariate approaches, including PCA-based analyses of metabolite variation (Jolliffe & Cadima, 2016; Rao et al., 2024), comparable integrated assessments for *M. oleifera* across elevation-associated sampling sites remain scarce. Previous moringa studies have generally emphasized individual chemical parameters rather than simultaneously evaluating multiple chemical traits within a unified statistical framework. Therefore, this study distinguishes itself by combining ANOVA, effect size estimation, correlation analysis, and PCA to examine multivariate patterns among nutritional, secondary metabolite, and structural characteristics of *M. oleifera* leaves across different elevation-associated environments. This approach allows assessment of both statistical differences and the relative contribution of each chemical trait to overall variation, while recognizing that site-specific environmental factors beyond elevation may also contribute to observed patterns.

Secondary metabolites, including phenolics and flavonoids, contribute to plant adaptation by mediating responses to environmental stress; however, their variation along elevation gradients is highly species-dependent and cannot be generalized across plant taxa. In *Moringa oleifera*, previous studies have mainly focused on nutritional value, antioxidant properties, or phytochemical composition under specific cultivation or environmental conditions (Stohs & Hartman, 2015). Although these studies have demonstrated substantial variation in protein, phenolic compounds, and bioactive constituents, they have rarely examined how multiple chemical components vary simultaneously across elevation-associated environments.

Recent elevation studies in other plant species have shown that multivariate approaches, including Principal Component Analysis (PCA), can reveal coordinated changes among nutritional, structural, and defense-related traits rather than evaluating individual metabolites separately (Jolliffe & Cadima, 2016; Rao et al., 2024). However, for *M. oleifera*, it remains unclear whether elevation-associated differences are accompanied by a consistent reorganization of chemical traits, particularly the relationship between growth-related components such as

protein and defense-related components such as tannins, phenolics, and flavonoids. Therefore, the unresolved question addressed in this study is whether elevation-associated sampling conditions are linked to integrated patterns of chemical variation in *M. oleifera* leaves when multiple biochemical parameters are analyzed simultaneously using complementary statistical approaches.

Furthermore, the variation in phenolic compounds across different elevations indicates that plants adjust their biochemical composition as part of an adaptive response to ecological pressures. This supports the hypothesis that environmental gradients, such as altitude, are key drivers of plant metabolic diversity (Gülsoy et al., 2023; Nataraj et al., 2022). Environmental factors, particularly altitude, play a crucial role in shaping plant physiological and biochemical characteristics. Variations in temperature, light intensity, and atmospheric pressure across altitudinal gradients significantly influence plant growth and metabolism. In particular, secondary metabolites such as flavonoids and phenolic compounds are known to respond dynamically to environmental stressors associated with elevation differences (Fu et al., 2022; Gülsoy et al., 2023).

Plants growing at higher altitudes are often exposed to increased ultraviolet radiation and lower temperatures, which can stimulate the production of protective compounds. These biochemical adjustments are essential for plant survival and adaptation, as they enhance antioxidant capacity and stress tolerance. Previous studies have demonstrated that altitudinal variation can significantly alter the concentration and composition of bioactive compounds in plants (Adhikari et al., 2022; Nataraj et al., 2022). Despite numerous studies on plant adaptation, there remains a gap in understanding how altitude specifically affects the balance between growth and secondary metabolite production in certain species. Therefore, this study aims to analyze the influence of altitude on plant biochemical characteristics, particularly focusing on flavonoid and phenolic content, as well as their ecological implications.

Based on these considerations, this study aims to evaluate whether chemical composition differs among *Moringa oleifera* leaf samples collected from different elevation-associated environments and to examine the relationships among nutritional, secondary metabolite, and structural traits using complementary statistical approaches. Specifically, this study tests the following hypotheses: (H1) protein content differs among elevation categories and is expected to decrease at higher elevation-associated sites; (H2) tannin content differs among elevation categories and is expected to increase at higher elevation-associated sites; (H3) total phenolic content differs among elevation categories, although the direction of response may vary because phenolic compounds represent diverse metabolic groups; (H4) flavonoid content differs among elevation categories and shows an elevation-associated response pattern; and (H5) crude fiber content differs among elevation categories and is expected to increase at higher elevation-associated sites.

In addition, this study hypothesizes that the combined variation among chemical traits will reflect a growth–defense allocation pattern, characterized by an inverse relationship between protein content and defense-related compounds such as tannins. This hypothesis is evaluated through correlation analysis and Principal Component Analysis (PCA), which identify associations among chemical traits rather than directly demonstrate underlying physiological mechanisms. By integrating univariate and multivariate analyses, this study provides an assessment of elevation-associated variation in *M. oleifera* leaf chemistry while recognizing that other site-specific environmental factors may also contribute to observed differences.

METHODS

This study was conducted in Kupang City and Kupang Regency from July to November 2024. The primary research material consisted of fresh moringa (*Moringa oleifera*) leaves collected from healthy plants of relatively uniform age at each sampling location. The chemicals used included standard reagents for the analysis of protein, tannins, total phenolics, flavonoids, and crude fiber. The equipment employed comprised an analytical balance, a drying oven, a blender or sample

grinder, and standard analytical chemistry laboratory instruments, including a UV-Vis spectrophotometer. **Experimental Design.** The experiment was arranged using a Completely Randomized Design (CRD) with a single treatment factor, namely elevation level. Three elevation categories were evaluated: 0–250 m above sea level (masl), 251–500 masl, and 501–750 masl. The experimental unit in this study was defined as an independent leaf sample collected from an individual moringa plant. Three biological replicates were obtained from separate plants within each elevation-associated category, resulting in nine independent samples ($n = 3$ per elevation category). Laboratory measurements were performed using these biological samples rather than being considered as independent replicates. Plants were selected based on comparable physiological conditions, including similar apparent age and health status. Because sampling locations represented different elevation-associated environments, the interpretation of elevation effects was limited to observed differences among sampled environments, and potential site-specific effects were considered as a limitation of the study.

Each treatment was replicated three times, resulting in a total of nine experimental units. **Sample Collection and Preparation.** Moringa leaves were harvested from the middle canopy of the plants to minimize physiological variability. The samples were cleaned to remove surface contaminants and oven-dried at a controlled temperature until a constant weight was achieved. The dried samples were then ground into a fine powder and stored in airtight containers prior to chemical analysis. **Chemical Analyses.** Chemical analyses were conducted to determine the protein, tannin, total phenolic, flavonoid, and crude fiber contents of moringa leaves. All analyses followed established and validated standard methods. Protein content was determined using the Kjeldahl method in accordance with AOAC 978.04, applying a nitrogen-to-protein conversion factor of 6.25. Crude fiber content was analyzed using the proximate method based on AOAC 978.10 (AOAC, 2019). Tannin content was measured using a colorimetric method based on the formation of phenolic complexes and expressed as a percentage (%). Total phenolic content was determined using the Folin–Ciocalteu method and expressed as milligrams of gallic acid equivalents per gram of sample (mg GAE/g). Flavonoid content was analyzed using an AlCl_3 -based spectrophotometric method and expressed as milligrams of quercetin equivalents per gram of sample (mg QE/g). All chemical analyses were performed in triplicate for each elevation level.

Data Analysis. The chemical composition data were analyzed using one-way analysis of variance (ANOVA) to assess the effect of elevation on each parameter. When significant differences were detected, Duncan's multiple range test was applied at a 95% confidence level ($\alpha = 0.05$). ANOVA calculations, Duncan's test, and effect size estimation using eta squared (η^2) were performed using Microsoft Excel supplemented with the Real Statistics Resource Pack. This software combination was used to ensure consistency in parametric statistical analyses and post hoc testing appropriate to the experimental design. Relationships among chemical parameters were evaluated using Pearson correlation analysis, with particular emphasis on the protein–tannin and total phenolic–flavonoid pairs. Correlation analyses were also conducted using the Real Statistics Resource Pack in Microsoft Excel. Principal Component Analysis (PCA) was subsequently performed using PAST (PAleontological STatistics) software. Prior to PCA, the data were standardized using z-scores. PCA was applied to identify multivariate patterns and relationships among the chemical parameters of moringa leaves across different elevation levels. The PCA results are presented as PC1–PC2 biplots displaying both sample scores and variable loadings (Abdi & Williams, 2010; Jolliffe & Cadima, 2016).

RESULT AND DISCUSSION

Protein Content

The results of protein content analysis of moringa leaves across the three elevation levels are presented in Figure 1. Protein content (%) of moringa leaves at different elevations ($n = 3$ per elevation)

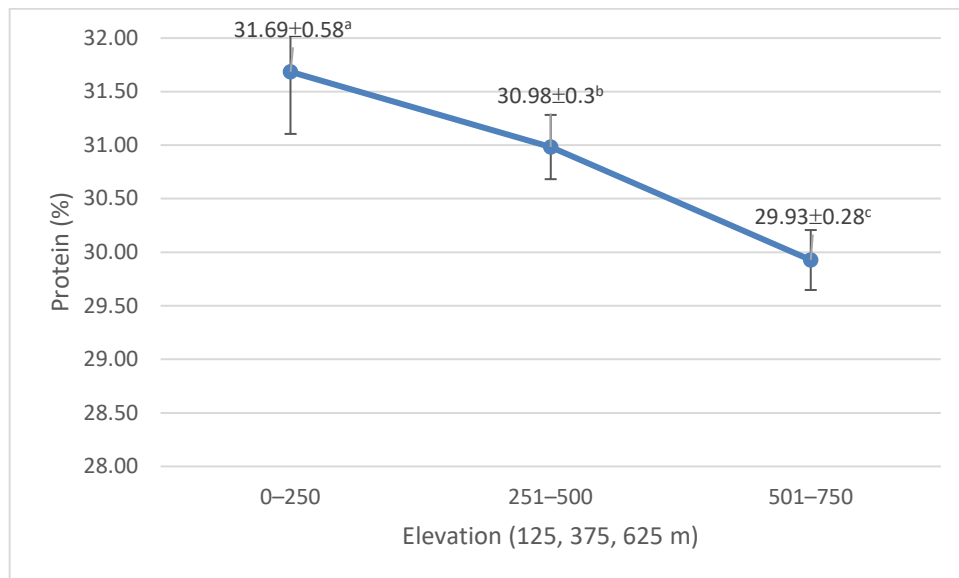


Figure 1. Protein content (%) of moringa leaves at different elevations (n = 3 per elevation)

Values are expressed as mean $\pm$ SD; different letters indicate significant differences according to Duncan's test ($\alpha = 0.05$).

One-way analysis of variance indicated statistical differences in protein content among the three sampled elevation classes ($F(2,6) = 13.98$; $p = 0.0055$). Mean protein content decreased across the sampled groups, from $31.69 \pm 0.58\%$ at 0–250 m asl to $30.98 \pm 0.30\%$ at 251–500 m asl and $29.93 \pm 0.28\%$ at 501–750 m asl. The corresponding 95% confidence intervals for the group means were approximately 30.25–33.13%, 30.23–31.73%, and 29.23–30.63%, respectively. Although the estimated between-group effect was large, it should not be interpreted as evidence that elevation itself controlled or caused the observed variation. Elevation class was associated with sampling location and potentially with other unmeasured factors, including soil properties, management practices, plant genotype, and local microclimate. Therefore, the present results demonstrate statistical separation among these sampled elevation groups rather than an independently estimated general effect of elevation. Given the small sample size (n = 3 per elevation class), both the effect-size estimate and its generalizability should be interpreted cautiously.

The reduction in protein content at higher elevations can be explained by several ecophysiological mechanisms. Lower temperatures and increased environmental stress at higher elevations generally reduce photosynthetic rates and vegetative growth, thereby limiting the capacity for primary protein synthesis (Nawaz et al., 2024). In addition, soil nitrogen availability and nitrogen uptake efficiency often decline with increasing elevation, or available nitrogen may be reallocated toward secondary metabolite production and structural components rather than protein synthesis.

This pattern is consistent with the growth–defense trade-off concept, in which plants reduce investment in growth-related traits and structural proteins while increasing the production of defensive compounds and reinforcing leaf structure under more stressful environmental conditions (Züst & Agrawal, 2017). This interpretation aligns with the overall findings of the present study, which show a simultaneous decrease in protein content alongside increases in tannins and crude fiber at higher elevations.

Recent studies have reported that the protein content of moringa leaves spans a wide range and is strongly influenced by growing conditions, including environmental factors and land management practices. (Rodrigues et al., 2023) reported significant variation in the protein content of *Moringa oleifera* leaves across different locations and cultivation conditions, although values generally remained nutritionally high. Similar trends have been observed in other plant species, where increasing elevation is associated with declines in growth-related and primary nutritional parameters (Filippi et al., 2021).

From a practical perspective, particularly for the use of moringa leaves as a nutritional resource, these results indicate that leaves harvested from lower elevations are more advantageous when high protein content is the primary objective. This information is valuable for planning cultivation sites and agronomic strategies, including nitrogen fertilization management, to optimize the nutritional quality of moringa leaves according to their intended use.

Total Phenolic Content

The results of total phenolic content analysis of moringa leaves across the three elevation levels are presented in Table 1.

Table 1. Total phenolic content (mg GAE/g) of moringa leaves at different elevations (n = 3 per elevation)

Elevation (m asl)	Total Phenolics (mg GAE g ⁻¹)
0–250	618.73 ± 69.45 ^a
251–500	545.75 ± 15.69 ^b
501–750	486.40 ± 45.78 ^c

Note. Values are expressed as mean ± SD; different letters indicate significant differences according to Duncan's test ($\alpha = 0.05$).

One-way analysis of variance indicated differences in total phenolic content among the three sampled elevation classes ($F(2,6) = 5.57$; $p = 0.042$). Total phenolic content decreased across the sampled groups, with mean values of 618.73 ± 69.45 mg GAE/g at 0–250 m asl, 545.75 ± 15.69 mg GAE/g at 251–500 m asl, and 486.40 ± 45.78 mg GAE/g at 501–750 m asl. The estimated effect size was $\eta^2 = 0.65$, indicating that elevation classes accounted for a substantial proportion of the observed variation; however, this estimate should be interpreted cautiously because of the limited sample size (n = 3 per elevation class). Post hoc comparison indicated that total phenolic content differed between the low-elevation and high-elevation groups (mean difference = 132.33 mg GAE/g; $p < 0.05$). The differences between 0–250 m and 251–500 m (mean difference = 72.98 mg GAE/g) and between 251–500 m and 501–750 m (mean difference = 59.35 mg GAE/g) should be interpreted according to the multiple comparison adjustment used in the post hoc test. Therefore, these findings indicate statistical separation among the sampled elevation groups rather than evidence that elevation alone caused the observed variation.

The decline in total phenolic content at higher elevations may be explained by differences in the regulation of the phenylpropanoid biosynthetic pathway. Under certain conditions, plants may redirect phenolic metabolic flux toward the synthesis of specific defensive compounds such as tannins, resulting in a decrease in measurable total phenolics even when particular fractions increase (Naikoo et al., 2019). In addition, reduced photosynthetic rates at higher elevations can limit energy availability, constraining the accumulation of total phenolics, which are relatively energy-intensive to synthesize. Several studies have shown that the response of total phenolics to elevation is not universal but strongly dependent on plant species and adaptive strategies. In some species, total phenolics increase at higher elevations as a response to enhanced UV radiation, whereas in others they decline due to limitations in growth and metabolic energy (López-Goldar et al., 2024).

The present findings are consistent with those reported by (Filippi et al., 2021), who demonstrated that changes in total phenolic content along elevation gradients are often mediated by shifts in growth rate and carbon allocation rather than by environmental stress alone. Other studies have similarly reported that in plants exhibiting increased levels of specific defensive metabolites, such as tannins, total phenolic content may decrease or remain relatively stable (Du et al., 2022). In the context of moringa leaves, the moderate variation in total phenolic content across elevations reflects the flexibility of the plant's secondary metabolism, allowing adjustments in phenolic composition in response to environmental conditions without a complete loss of antioxidant capacity (Rodrigues et al., 2023).

From an application perspective, the higher total phenolic content observed at low to mid elevations suggests that moringa leaves from these locations may be more suitable as sources of natural antioxidants. This information is particularly relevant for selecting cultivation sites when the primary objective is the development of functional foods or raw materials with high antioxidant activity.

Flavonoid Content

The results of flavonoid content analysis of moringa leaves across the three elevation levels are presented in Table 2.

Table 2. Flavonoid content (mg QE/g) of moringa leaves at different elevations (n = 3 per elevation)

Elevation (m asl)	Flavonoids (mg QE g⁻¹)
0–250	2.83 ± 0.11 ^a
251–500	1.85 ± 0.14 ^b
501–750	1.51 ± 0.06 ^c

Note. Values are expressed as mean ± SD; different letters indicate significant differences according to Duncan's test ($\alpha = 0.05$).

One-way analysis of variance showed that elevation had a significant effect on the flavonoid content of moringa leaves ($p < 0.01$). The effect size (η^2) was in the large category, indicating that differences in elevation made a substantial contribution to the variation in flavonoid content among samples. The results demonstrate a consistent decline in flavonoid content with increasing elevation. The highest flavonoid concentration was observed at low elevation (0–250 m asl), followed by a significant decrease at medium and high elevations. This trend parallels that of total phenolics but contrasts with the pattern observed for tannins, which increased at higher elevations. These contrasting trends suggest that flavonoids and tannins respond to elevation through different adaptive mechanisms.

The reduction in flavonoid content at higher elevations can be linked to limitations in metabolic energy associated with reduced photosynthetic rates and vegetative growth. Flavonoid biosynthesis is relatively energy-intensive; therefore, under more stressful environmental conditions, plants may redirect carbon allocation toward structural defenses or other secondary metabolites that provide longer-term protective benefits, such as tannins (Naikoo et al., 2019). In addition, flavonoid regulation is strongly influenced by the balance between protection against radiation and the overall metabolic demands of the plant. In some species, flavonoid levels increase at higher elevations as a response to enhanced UV radiation; however, in other species particularly tropical plants flavonoid content may decline due to constraints on growth and metabolic energy (López-Goldar et al., 2024). The present results indicate that moringa leaves tend to follow the latter pattern.

These findings are consistent with the report by Bhuker et al., (2023), who noted that flavonoid responses to environmental factors are highly species-specific and do not necessarily increase in parallel with total phenolics or tannins. Bhuker et al., (2023) similarly reported that changes in flavonoid content along elevation gradients are often mediated by variations in leaf growth rates and carbon allocation rather than by environmental stress alone. In functional plants, variations in flavonoid content often reflect a balance between antioxidant capacity and metabolic efficiency. Accordingly, a reduction in flavonoids at higher elevations does not necessarily imply a decrease in overall defensive capacity but may indicate a shift in the plant's chemical defense strategy.

From a utilization perspective, the higher flavonoid content observed in moringa leaves from low elevations suggests greater potential as a source of natural antioxidants for functional foods or supplements. Conversely, leaves from higher elevations may be more suitable for applications emphasizing structural resilience or other defensive compounds, albeit with relatively lower flavonoid levels.

Crude Fiber Content

The results of crude fiber content analysis of moringa leaves across the three elevation levels are presented in Table 3.

Table 3. Crude fiber content (%) of moringa leaves at different elevations (n = 3 per elevation)

Elevation (m asl)	Crude Fiber (%)
0–250	4.91 ± 0.45 ^c
251–500	5.72 ± 0.25 ^b
501–750	7.81 ± 0.96 ^a

Note. Values are expressed as mean ± SD; different letters indicate significant differences according to Duncan's test ($\alpha = 0.05$).

One-way analysis of variance showed that elevation had a significant effect on the crude fiber content of moringa leaves ($p < 0.01$). The effect size (η^2) was in the large category, indicating that elevation contributed substantially to the observed variation in crude fiber content. The results reveal a consistent increase in crude fiber content with increasing elevation. The lowest crude fiber level was recorded at 0–250 m asl, followed by a significant increase at mid elevation, with the highest value observed at 501–750 m asl. This pattern mirrors the increase in tannin content and contrasts with the declining trend in protein content, indicating a shift in moringa leaf adaptive strategy from growth toward enhanced structural reinforcement and defense at higher elevations.

The increase in crude fiber at higher elevations can be explained as a morphostructural adaptation to more extreme environmental conditions. Lower temperatures, greater wind exposure, and nutrient limitations at higher elevations promote increased lignification and thickening of cell walls to maintain leaf tissue integrity (Onoda et al., 2017). While this process enhances crude fiber content, it is often accompanied by a reduction in nutritional quality, particularly protein concentration. Moreover, the observed increase in crude fiber is closely related to the leaf economics spectrum concept, which posits that leaves in more stressful environments tend to be thicker, tougher, and longer-lived, but exhibit lower growth rates and reduced nutrient content (Poorter et al., 2009). This framework is consistent with the present findings, which show increasing crude fiber alongside decreasing protein content at higher elevations.

Several studies published in the last five years have reported that fiber content and other structural components of leaves increase along more extreme environmental gradients, including higher elevations. Du et al., (2022) demonstrated that increasing elevation is associated with enhanced structural investment and a decline in nutritional traits across various plant organs. Similar patterns have been documented in ecophysiological studies emphasizing lignification as a key adaptive mechanism to environmental stress (Onoda et al., 2017). In functional plants such as moringa, higher crude fiber content can confer structural advantages and increased resilience but may also reduce digestibility and nutritional value when leaves are used as food or feed without adequate processing (Rodrigues et al., 2023).

From a utilization perspective, moringa leaves harvested from higher elevations, with their higher crude fiber content, may be more suitable for applications emphasizing structural function or dietary fiber. In contrast, for food or feed purposes that prioritize digestibility and protein content, leaves from low to mid elevations are more strongly recommended.

Correlation between Protein and Tannin

Pearson correlation analysis revealed a strong negative correlation between protein and tannin contents in moringa leaves. This relationship indicates that increases in tannin concentration are generally accompanied by decreases in protein content (Figure 2).

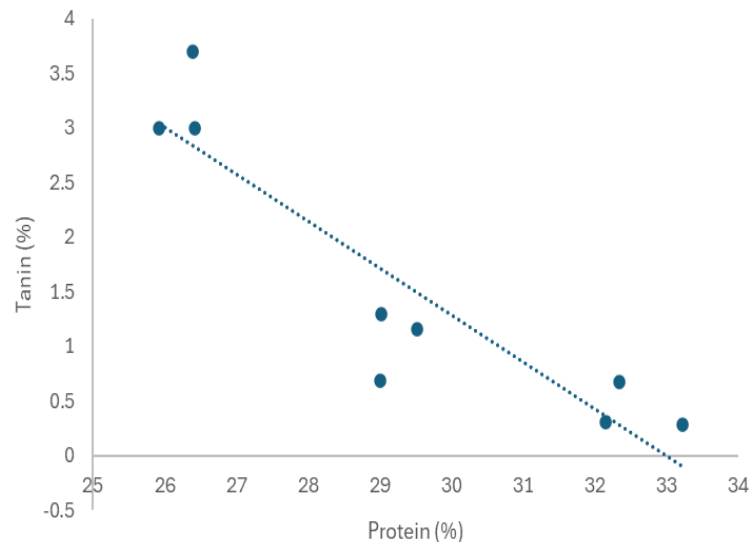


Figure 2. Relationship between protein and tannin contents in moringa leaves

From a physiological perspective, the negative protein–tannin correlation reflects a trade-off between plant growth and defense, whereby metabolic resources are alternately allocated to protein synthesis (primary metabolism) and the production of defensive compounds such as tannins (secondary metabolism). This pattern is well described by the growth–defense trade-off theory, which posits that increased investment in defensive compounds typically occurs at the expense of growth rate and biomass accumulation (Herms & Mattson, 1992).

A number of contemporary studies similarly report that tannin production and other phenolic defenses increase under environmentally stressful conditions, while the synthesis of structural and enzymatic proteins declines due to limitations in energy and nutrient availability (Neilson et al., 2013). Accordingly, the negative protein–tannin correlation observed in this study supports physiological mechanisms that have been widely documented in plant ecology and plant physiology literature.

Correlation between Total Phenolics and Flavonoids

Pearson correlation analysis indicated a positive association between total phenolic content and flavonoid content in moringa leaves ($r = 0.822$, 95% CI: 0.30–0.96, $p = 0.006$, $n = 9$). The coefficient of determination from the linear regression model ($R^2 = 0.676$) indicated that approximately 67.6% of the variation in flavonoid content was associated with variation in total phenolic content within the sampled observations. However, this relationship should be interpreted cautiously because the analysis was based on only nine observations collected from three elevation classes, and observations within elevation groups may share site-related characteristics. The observed association may reflect the shared biosynthetic origin of flavonoids and other phenolic compounds through the phenylpropanoid pathway. However, the present correlation analysis cannot distinguish whether the relationship results from coordinated regulation, shared environmental responses, or other unmeasured factors. Similar patterns have been reported in various plant species, where flavonoids account for only part of the variation in total phenolic content (Bhuker et al., 2023).

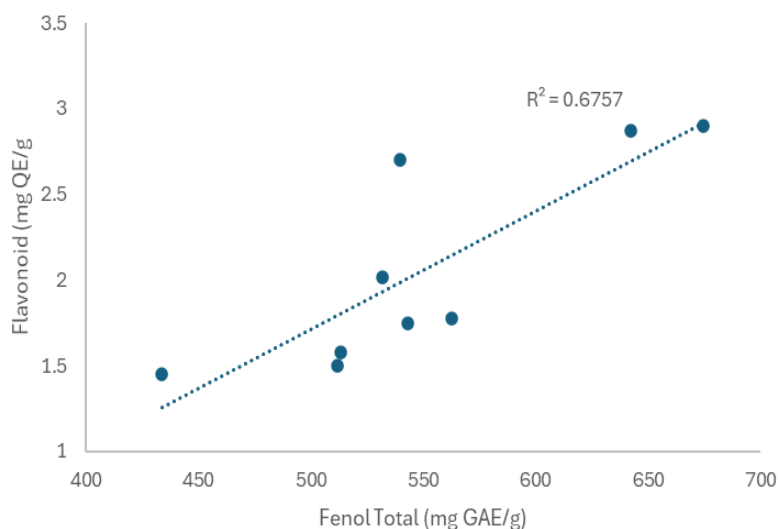


Figure 3. Relationship between total phenolic and flavonoid contents in moringa leaves

Principal Component Analysis of Chemical Composition

Principal Component Analysis (PCA) was performed using nine independent biological observations and five standardized chemical variables (protein, tannin, total phenolic content, flavonoids, and crude fiber). No missing values were present, and therefore no data imputation was applied. The PCA was conducted on the correlation matrix after z-score standardization because the variables were measured on different scales. PCA enables the integration of all measured variables within a single analytical framework, allowing dominant patterns of chemical variation to be identified simultaneously while reducing redundancy among correlated variables (Jolliffe & Cadima, 2016). The PCA results showed that the first two principal components accounted for most of the variation in the chemical dataset. The first principal component (PC1) explained 86.34% of the total variance, while the second principal component (PC2) explained 7.62%, resulting in a cumulative variance of 93.97% (Figure 4). This high cumulative value indicates that the data structure is relatively simple and can be adequately represented in a two-dimensional space (Abdi & Williams, 2010).

A sensitivity analysis was performed to evaluate the stability of PCA interpretation. The general loading pattern, particularly the opposite contribution of protein versus tannin and crude fiber along PC1, remained consistent across repeated analyses. Therefore, PCA provides descriptive evidence of chemical pattern separation among the sampled groups but should not be interpreted as confirmation of a causal elevation-driven mechanism.

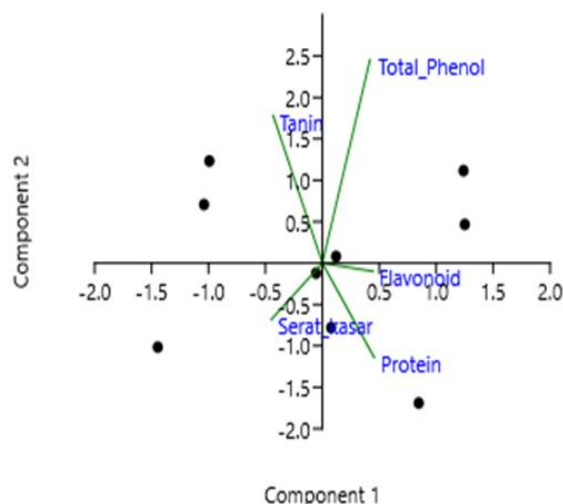


Figure 4. PCA biplot (PC1 vs PC2) of moringa leaf chemical composition across elevation levels

In the PCA biplot, PC1 clearly separated samples along the elevation gradient. Tannins and crude fiber showed strong positive loadings on PC1, whereas protein exhibited a strong negative loading. This pattern highlights a sharp contrast between defense/structural components and nutritional components. The result is consistent with the growth–defense trade-off concept, in which plants reallocate resources from growth-related processes toward defense under more stressful environmental conditions (Herms & Mattson, 1992; Neilson et al., 2013). The second principal component (PC2) was primarily influenced by total phenolic content, indicating that variation in total phenolics is relatively independent of the main protein–tannin gradient captured by PC1. This suggests that total phenolics represent an additional chemical dimension related to antioxidant capacity and oxidative stress responses, rather than being directly associated with growth or structural defense alone (Naikoo et al., 2019).

Flavonoids showed relatively smaller loadings and were positioned closer to the center of the biplot, indicating a more moderate contribution to the primary separation of samples. This finding is consistent with the univariate results, which showed that flavonoids respond to elevation, but less strongly than tannins or crude fiber. Similar moderate and context-dependent flavonoid responses to environmental gradients have been reported in various plant species (Agati et al., 2012). The distribution of sample scores on the PCA biplot further revealed that samples from low elevation (0–250 m asl) were associated with higher protein content, whereas samples from high elevation (501–750 m asl) were associated with higher tannin and crude fiber contents. Samples from the intermediate elevation occupied a transitional position between these two groups. This pattern reinforces the conclusion that elevation is the dominant factor controlling chemical variation in moringa leaves, as also demonstrated by the ANOVA, Duncan's test, and correlation analyses.

Overall, the PCA results were consistent with the univariate analyses and provided a multivariate visualization of the relationships among chemical traits in moringa leaves. The PCA indicated a separation between nutritional attributes and structural/defense-related traits, with protein showing an opposite pattern to tannin and crude fiber along the main component axis. However, the chemical responses were not uniform across all secondary metabolites. While tannin and crude fiber increased at higher elevations, total phenolic and flavonoid contents showed decreasing trends across the sampled elevation classes. Therefore, the PCA results should be interpreted as indicating coordinated variation among specific chemical traits rather than a universal elevation-driven increase in defensive compounds. Because elevation classes were associated with sampling locations and other potentially confounding environmental factors, these findings represent multivariate patterns among the sampled groups rather than confirmation of a general causal elevation effect.

The differences in phenolic content observed in this study further support the notion that environmental factors significantly affect plant biochemical traits. Similar patterns have been reported in other plant species, where altitude was found to influence antioxidant activity and phenolic composition (Gülsoy et al., 2023). Moreover, the variation in secondary metabolites can be interpreted as part of a broader ecological adaptation strategy. Plants adjust their chemical composition not only to cope with abiotic stress but also to optimize interactions with their environment. This is in line with findings that highlight the role of phenolic and volatile compounds in ecological adaptation across altitudinal gradients (Nataraj et al., 2022).

In summary, the findings of this study demonstrate that altitudinal gradients exert a substantial influence on plant biochemical characteristics, particularly in shaping the accumulation of flavonoids and phenolic compounds. These variations are not merely incidental but reflect a coordinated adaptive response to environmental pressures such as increased ultraviolet radiation, temperature fluctuations, and ecological constraints. The consistency between the present findings and previous studies reinforces the understanding that secondary metabolites function as critical components in plant resilience and survival strategies.

More importantly, this study contributes to understanding how elevation-associated environmental variation is related to the chemical composition of *Moringa oleifera* leaves. The

observed patterns indicate that sampled elevation classes were associated with differences in nutritional, secondary metabolite, and structural chemical traits, particularly the decrease in protein content and the increase in tannin and crude fiber contents at higher elevations. However, the present study did not directly evaluate agronomic performance, pharmacological activity, antioxidant capacity, digestibility, or environmental management outcomes. Therefore, potential applications of these chemical patterns for food, feed, or bioactive compound utilization should be considered as future research directions rather than demonstrated outcomes. Further studies integrating physiological measurements, functional bioactivity assays, nutritional evaluation, and multi-site environmental characterization are required to determine the practical implications of elevation-related variation in moringa leaf composition.

Nevertheless, this study has several design-specific limitations that should be considered when interpreting the findings. First, the number of independent biological units was limited, with only three sampled elevation classes and three replicates per class ($n = 9$). Therefore, estimates of effect size, correlation coefficients, and multivariate patterns may have relatively high uncertainty and should be interpreted cautiously. Second, elevation was evaluated through naturally occurring sampling locations rather than experimental manipulation, meaning that elevation class may be confounded with site-specific characteristics. Differences among groups may therefore reflect not only elevation-associated variation but also unmeasured location effects.

In addition, soil properties and microclimatic variables, such as nutrient availability, soil moisture, temperature, and radiation conditions, were not directly measured. Consequently, the physiological mechanisms underlying the observed chemical differences cannot be confirmed from the present dataset. Although samples were collected from plants with relatively similar characteristics, plant genotype and exact age were not independently verified, and potential genetic or developmental variation may have contributed to the observed patterns. Furthermore, the study was conducted within a limited geographic area and sampling period, which restricts the generalization of the results to other environments, seasons, or cultivation systems.

Finally, correlation analysis and PCA were based on a small number of observations, making these estimates potentially sensitive to individual data points. Therefore, the correlation structures and PCA patterns should be regarded as exploratory descriptions of chemical relationships among the sampled leaves rather than definitive evidence of general ecological mechanisms. Future studies incorporating replicated sites within each elevation class, larger sample sizes, longitudinal sampling, and direct measurements of environmental and plant-related covariates are needed to validate the observed associations.

Discussion

This study demonstrates that Fear of Missing Out (FoMO), online social comparison, and self-identity formation operate as interconnected psychosocial processes among early adolescents in Indonesian junior secondary schools. FoMO was expressed not simply as apprehension about missing information, but as anxiety about being absent from peer conversations, viral trends, and digitally mediated group belonging. This pressure encouraged repeated checking, rapid responses to peer activity, and trend-based self-presentation. At the same time, upward comparison with peers and influencers widened the perceived distance between participants' actual and ideal selves, making self-evaluation increasingly dependent on likes, comments, views, and other visible indicators of approval. In identity-development terms, these processes were associated predominantly with anxious forms of moratorium and premature foreclosure rather than stable, self-directed identity achievement. Thus, the findings answer the study objectives by showing that FoMO shapes both the process of exploration through digitally cued experimentation and self-curation and the process of commitment through conformity to identities that receive social validation.

These findings are consistent with, but also add nuance to, recent global research. FoMO was linked with problematic social media use through a serial pathway involving social

comparison and lower self-esteem. The present qualitative findings provide developmental texture to these statistical relationships: for early adolescents, comparison and self-esteem are not only psychological correlates but are embedded in the ongoing construction of “who I am” and “who I should become.” However, the results caution against treating social media exposure as uniformly harmful. Beyens et al. (2020) showed marked person-specific variation in adolescents’ affective responses to passive social media use, and Boer et al. (2020), in 29 countries, distinguished between intense use which may be normative in some contexts and problematic use, which was more consistently associated with poorer well-being. Coyne et al. (2020) likewise found no simple longitudinal link between time spent on social media and later depression or anxiety. Thus, the salient issue is not screen time *per se*, but the quality and meaning of use: compulsive synchronization with peers, metric-based validation, upward comparison, and dependence on externally curated standards. This interpretation is reinforced by person-specific work showing that social media effects on self-esteem and friendship closeness vary substantially among adolescents (Pouwels et al., 2021; Valkenburg et al., 2021) and by umbrella-review evidence emphasizing the interaction of user characteristics, type of use, content, and platform design (Sala et al., 2024).

The identity-related findings also converge with research on online self-disclosure and digitally mediated relationships. Towner et al. (2022) concluded that self-disclosure can support relationship quality and well-being, yet online disclosure may be less relationally fulfilling than face-to-face disclosure, whereas Bottaro and Faraci (2022) documented both benefits and risks of social networking for adolescent emotional well-being. In Vietnam, Ho and Nguyen (2023) showed that online self-disclosure could become linked to loneliness and psychological distress through cybervictimization, illustrating how apparently expressive practices acquire different consequences depending on the surrounding social environment. In a non-Western comparison particularly relevant to the present study, Sharma and Gera (2025) found among 42 Indian adolescents that online disinhibition facilitated emotional expression and parasocial bonds that contributed to identity exploration and emotional regulation. Both studies frame digital environments as identity spaces in collectivist settings, but the mechanism differs: Sharma and Gera foreground parasocial attachment and emotional substitution, whereas the Indonesian participants in this study were more strongly organized around peer visibility, trend participation, and quantifiable feedback. Research from India and East Asia further indicates that parental influence and peer norms can shape adolescents’ cyber-behavior (Achuthan et al., 2022; Park et al., 2021), while qualitative evidence from adolescent girls shows that digital environments can simultaneously provide support and impose relational limitations (Mackenzie et al., 2020). Accordingly, culture interacts with platform affordances and developmental sensitivity to belonging rather than functioning as a fixed explanation.

Within Indonesia, the findings confirm but extend a growing body of evidence on FoMO and comparison. Unlike these predominantly correlational studies, this study shows how the mechanism is experienced in school life: being disconnected can be interpreted as social absence, and visible engagement metrics can become cues for self-worth and identity adjustment. This contextual interpretation is also compatible with Ramadhan et al. (2026), who show that adolescent socialization in Indonesia increasingly unfolds within algorithmically structured social media environments and argue that family mediation must evolve alongside such environments. The local contribution is therefore an explanation of how peer-oriented belonging, algorithmic visibility, and external validation become woven into identity exploration in an urban junior-secondary-school setting.

Theoretically, pedagogically, and at the policy level, the findings point to the same central proposition: adolescent digital well-being depends less on eliminating digital participation than on strengthening reflective agency within it. Theoretically, the results extend Erikson’s psychosocial account, Marcia’s identity-status model, and self-discrepancy theory by suggesting a digitally intensified form of moratorium in which exploration can be abundant but weakly self-authored, while premature foreclosure can occur when commitment is guided by peer-approved

trends and algorithmically amplified ideals. Platform metrics thus become visible cues through which the ideal self is recalibrated. Pedagogically, schools should therefore move beyond technical e-safety toward critical media literacy, emotional literacy, digital citizenship, and reflective identity work. Recent research supports teaching media literacy and digital citizenship as connected competencies (von Gillern et al., 2024), while a recent meta-analysis suggests that media-literacy capacities particularly analytical and evaluative dimensions may have a positive relationship with well-being, although causal conclusions remain premature (Gordon et al., 2025). The shift from protectionist to participatory, critical media education proposed by Jumakulova and Kushieva (2025) is especially relevant: students can be taught to interrogate engagement metrics, influencer curation, algorithmic recommendation, comparison triggers, privacy boundaries, and the distinction between authentic exploration and conformity-driven performance. Although classroom engagement was not directly measured, Indonesian educational-media research by Koderi et al. (2023), Sufian et al. (2023), and Pribowo et al. (2024) demonstrates that well-designed, culturally contextualized, and interactive digital media can support engagement and learning; this reinforces the case for guided rather than purely restrictive digital practice. At the policy level, schools and education systems should integrate age-appropriate digital well-being curricula, counselor-led preventive interventions, and structured family-school collaboration. Platform-level policy should also consider youth-sensitive privacy defaults, greater transparency around recommender and engagement systems, and independent research access to platform data, consistent with calls for responsible platform design (Sala et al., 2024). In the Indonesian context, family mediation should be dialogical rather than solely prohibitive (Ramadhan et al., 2026), while digital-ethics policy should also respect privacy and psychosocial safety in family communication (Edi & Alghifari, 2026). These are evidence-informed recommendations, not effects directly tested by this qualitative design.

The novelty of this study lies in integrating FoMO, online social comparison, self-discrepancy, and identity-status processes within a qualitative account of early adolescence in an Indonesian school context. Whereas much of the existing literature models FoMO as an antecedent of problematic use, fatigue, self-esteem reduction, or other psychosocial outcomes, this study positions it as a developmental catalyst that can restructure the conditions under which identity exploration and commitment occur. Methodologically, preliminary screening, interviews, school-based observations, field notes, and ethically bounded digital-trace analysis triangulate reported and observed practices. Conceptually, the findings move beyond the binary proposition that social media is either beneficial or harmful and instead show how identity outcomes depend on the interaction between developmental vulnerability, peer culture, platform affordances, and reflective capacity. This context-sensitive account bridges identity theory, FoMO research, media-effects scholarship, and critical digital-literacy practice.

Several limitations qualify these interpretations. First, 27 focal participants from three public junior secondary schools in South Surabaya limit transferability to other regions, school types, and socioeconomic groups. Second, the cross-sectional design cannot establish causal ordering or determine whether the observed identity patterns persist over time. Third, purposive selection of highly active social media users appropriately served the study objectives but may overrepresent adolescents for whom digital pressures are especially salient. Fourth, interviews and observations remain vulnerable to social-desirability effects and reactivity, while ethical restrictions on digital-content access mean that private, deleted, or alternative-account behavior may be underrepresented. The study also did not clinically assess mental-health disorders or directly measure classroom engagement, so implications for mental health and academic participation should not be interpreted diagnostically or causally. Future research should employ longitudinal and mixed-method designs, experience-sampling methods, validated psychometric measures, and where ethically feasible participant-controlled platform-use data. Comparative studies across school types, regions, gender groups, socioeconomic contexts, and countries would test the cultural portability of the proposed mechanisms. Intervention studies should further evaluate whether critical media-literacy curricula, reflective identity mapping,

counseling modules, and family–school mediation reduce maladaptive comparison and FoMO while supporting self-esteem, emotional regulation, healthy engagement, and more autonomous identity commitment.

CONCLUSION

This study demonstrates that the sampled elevation classes were associated with variation in the chemical composition of *Moringa oleifera* leaves. Protein content showed a decreasing pattern across elevation classes, from $31.69 \pm 0.58\%$ at 0–250 m asl to $29.93 \pm 0.28\%$ at 501–750 m asl, whereas tannin and crude fiber contents increased with increasing elevation. In contrast, total phenolic and flavonoid contents showed decreasing trends at higher elevations, indicating that secondary metabolites did not exhibit a uniform response pattern. Multivariate analysis through PCA revealed separation among chemical traits, particularly the contrasting distribution of protein relative to tannin and crude fiber, but these patterns should be interpreted as associations among sampled groups rather than confirmation of a causal elevation-driven mechanism.

The interpretation of these findings is constrained by the observational design, limited sample size (three replicates per elevation class; $n = 9$), and the potential influence of unmeasured site-level factors, including soil properties, microclimate, genotype, and plant developmental variation. Therefore, the observed chemical differences represent patterns within the sampled locations and should not be generalized as a universal elevation effect without further validation. The potential implications of these chemical profiles for food, feed, or bioactive compound utilization remain hypotheses requiring evaluation through replicated multisite studies, functional assays, and direct measurements of environmental and physiological variables.

REFERENCE

- Abdi, H., & Williams, L. J. (2010). Principal component analysis. *Wiley Interdisciplinary Reviews: Computational Statistics*, 2(4), 433–459. <https://doi.org/10.1002/wics.101>
- Achuthan, K., Muthupalani, S., Kolil, V. K., & Madathil, K. C. (2022). Theoretical perspectives of parental influence on adolescent cyber behaviour: A bi-national Instagram-based study. *Heliyon*, 8(11), Article e11813. <https://doi.org/10.1016/j.heliyon.2022.e11813>
- Adhikari, P., Joshi, K., Singh, M., & Pandey, A. (2022). Influence of altitude on secondary metabolites and antioxidant activity of *Taxus wallichiana*. *Plant Biosystems*, 156(1), 187–195. <https://doi.org/10.1080/11263504.2020.1845845>
- Agati, G., Azzarello, E., Pollastri, S., & Tattini, M. (2012). Flavonoids as antioxidants in plants: Location and functional significance. *Plant Science*, 196, 67–76. <https://doi.org/10.1016/j.plantsci.2012.07.014>
- AOAC International. (2019). *Official methods of analysis of AOAC International* (21st ed.).
- Beyens, I., Pouwels, J. L., van Driel, I. I., Keijsers, L., & Valkenburg, P. M. (2020). The effect of social media on well-being differs from adolescent to adolescent. *Scientific Reports*, 10, Article 10763. <https://doi.org/10.1038/s41598-020-67727-7>
- Bhuker, A., Malik, A., Punia, H., McGill, C., Sofkova-Bobcheva, S., Mor, V. S., Singh, N., Ahmad, A., & Mansoor, S. (2023). Probing the phytochemical composition and antioxidant activity of *Moringa oleifera* under ideal germination conditions. *Plants*, 12(16), Article 3010. <https://doi.org/10.3390/plants12163010>
- Boer, M., van den Eijnden, R. J. J. M., Boniel-Nissim, M., Wong, S.-L., Inchley, J. C., Badura, P., Craig, W. M., Gobina, I., Kleszczewska, D., Klanšček, H. J., & Stevens, G. W. J. M. (2020). Adolescents' intense and problematic social media use and their well-being in 29 countries. *Journal of Adolescent Health*, 66(6 Suppl.), S89–S99. <https://doi.org/10.1016/j.jadohealth.2020.02.014>
- Bottaro, R., & Faraci, P. (2022). The use of social networking sites and its impact on adolescents' emotional well-being: A scoping review. *Current Addiction Reports*, 9(4), 518–539. <https://doi.org/10.1007/s40429-022-00445-4>
- Cope, O. L., Keefover-Ring, K., Kruger, E. L., & Lindroth, R. L. (2021). Growth–defense trade-offs

- shape population genetic composition in an iconic forest tree species. *Proceedings of the National Academy of Sciences*, 118(23), Article e2103162118. <https://doi.org/10.1073/pnas.2103162118>
- Coyne, S. M., Rogers, A. A., Zurcher, J. D., Stockdale, L., & Booth, M. (2020). Does time spent using social media impact mental health? An eight year longitudinal study. *Computers in Human Behavior*, 104, Article 106160. <https://doi.org/10.1016/j.chb.2019.106160>
- Du, Z., Lin, W., Yu, B., Zhu, J., & Li, J. (2022). Integrated metabolomic and transcriptomic analysis of the flavonoid accumulation in the leaves of *Cyclocarya paliurus* at different altitudes. *Frontiers in Plant Science*, 12, Article 794137. <https://doi.org/10.3389/fpls.2021.794137>
- Edi, R. N., & Alghifari, A. (2026). Protection of family privacy in Islamic law: A review of the prohibition against exposing household faults. *Gender, Islamic Law, and Sustainability*, 1(2), 133–149. <https://doi.org/10.70211/gils.v1i2.390>
- Filippi, A., Braidot, E., Petrusa, E., Fabro, M., Vuerich, M., & Boscutti, F. (2021). Plant growth shapes the effects of elevation on the content and variability of flavonoids in subalpine bilberry stands. *Plant Biology*, 23(2), 241–249. <https://doi.org/10.1111/plb.13194>
- Fu, S., Deng, Y., Zou, K., Zhang, S., Liu, X., & Liang, Y. (2022). Flavonoids affect the endophytic bacterial community in *Ginkgo biloba* leaves with increasing altitude. *Frontiers in Plant Science*, 13, Article 982771. <https://doi.org/10.3389/fpls.2022.982771>
- Gordon, C. S., Ferber, K., Notley, T., Rodgers, R. F., Bradshaw, E., Basarkod, G., Anderson, J., McLean, S. A., Mizzi, S., Jarman, H. K., Dickson, J., Sanders, T., Slater, A., Pearson, E., & Dicke, T. (2025). The relationship between media literacy and well-being: A systematic review and meta-analysis. *Educational Research Review*, 49, Article 100731. <https://doi.org/10.1016/j.edurev.2025.100731>
- Gülsoy, E., Kaya, E. D., & Türkhan, A. (2023). The effect of altitude on phenolic, antioxidant and fatty acid compositions of hazelnut cultivars. *Molecules*, 28(13), Article 5067. <https://doi.org/10.3390/molecules28135067>
- Herms, D. A., & Mattson, W. J. (1992). The dilemma of plants: To grow or defend. *The Quarterly Review of Biology*, 67(3), 283–335. <https://doi.org/10.1086/417659>
- Ho, T. T. Q., & Nguyen, H. T. (2023). Self-disclosure on social networking sites, loneliness and psychological distress among adolescents: The mediating effect of cyber victimization. *European Journal of Developmental Psychology*, 20(1), 172–188. <https://doi.org/10.1080/17405629.2022.2068523>
- Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: A review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374(2065), Article 20150202. <https://doi.org/10.1098/rsta.2015.0202>
- Jumakulova, N. R., & Kushieva, N. K. (2025). The evolution of media education methodologies: From traditional approaches to modern innovations. *Digital Learning, Social Science, and Life-course Studies*, 1(2), 107–118. <https://doi.org/10.70211/disolife.v1i2.341>
- Koderi, Sufian, M., & Erlina. (2023). Developing Lampung local wisdom film of Arabic communication skills for Madrasah Tsanawiyah students. *International Journal of Information and Education Technology*, 13(12), 2004–2013. <https://doi.org/10.18178/ijiet.2023.13.12.2015>
- López-Goldar, X., Zhang, X., Hastings, A. P., Duplais, C., & Agrawal, A. A. (2024). Plant chemical diversity enhances defense against herbivory. *Proceedings of the National Academy of Sciences*, 121(51), Article e2417524121. <https://doi.org/10.1073/pnas.2417524121>
- Mackenzie, E., McMaugh, A., & Van Bergen, P. (2020). Digital support seeking in adolescent girls: A qualitative study of affordances and limitations. *Cyberpsychology: Journal of Psychosocial Research on Cyberspace*, 14(3), Article 5. <https://doi.org/10.5817/CP2020-3-5>
- Naikoo, M. I., Dar, M. I., Raghieb, F., & Jaleel, H. (2019). Role and regulation of plants phenolics in abiotic stress tolerance. *Plant Signaling & Behavior*, 14(8), Article 1596719. <https://doi.org/10.1080/15592324.2019.1596719>
- Nataraj, N., Hussain, M., & Ibrahim, M. (2022). Effect of altitude on volatile organic and phenolic compounds of *Artemisia brevifolia*. *Frontiers in Ecology and Evolution*, 10, Article 864728. <https://doi.org/10.3389/fevo.2022.864728>
- Nawaz, A., Walayat, N., Khalifa, I., Harlina, P. W., Irshad, S., Qin, Z., & Luo, X. (2024). Emerging challenges and efficacy of polyphenols–proteins interaction in maintaining the meat safety

- during thermal processing. *Comprehensive Reviews in Food Science and Food Safety*, 23(2), Article e13313. <https://doi.org/10.1111/1541-4337.13313>
- Neilson, E. H., Goodger, J. Q. D., & Woodrow, I. E. (2013). Plant chemical defense: At what cost? *Trends in Plant Science*, 18(5), 250–258. <https://doi.org/10.1016/j.tplants.2013.02.001>
- Onoda, Y., Westoby, M., & Adler, P. B. (2017). Global patterns of leaf mechanical properties. *Ecology Letters*, 20(6), 728–739. <https://doi.org/10.1111/ele.12763>
- Park, M. S.-A., Golden, K. J., Vizcaino-Vickers, S., Jidong, D., & Raj, S. (2021). Sociocultural values, attitudes and risk factors associated with adolescent cyberbullying in East Asia: A systematic review. *Cyberpsychology: Journal of Psychosocial Research on Cyberspace*, 15(1), Article 5. <https://doi.org/10.5817/CP2021-1-5>
- Poorter, H., Niinemets, Ü., & Poorter, L. (2009). Causes and consequences of variation in leaf mass per area (LMA). *New Phytologist*, 182(3), 565–588. <https://doi.org/10.1111/j.1469-8137.2009.02830.x>
- Pouwels, J. L., Valkenburg, P. M., Beyens, I., van Driel, I. I., & Keijsers, L. (2021). Social media use and friendship closeness in adolescents' daily lives: An experience sampling study. *Developmental Psychology*, 57(2), 309–323. <https://doi.org/10.1037/dev0001148>
- Pribowo, M. A., Hadiati, E., Koderi, & Sufian, M. (2024). Pengembangan e-modul Pendidikan Agama Islam interaktif berbasis Flipbook untuk meningkatkan pembelajaran di sekolah menengah pertama. *Jurnal PAI Raden Fatah*, 6(4), 961–974. <https://doi.org/10.19109/pairf.v6i4.24668>
- Ramadhan, R. M., Sekarningrum, B., & Nurwati, N. (2026). Constructing adolescent sexual education in algorithmic social media ecosystems: Family as a socializing agent. *JPI: Jurnal Pustaka Indonesia*, 6(2), 13–27. <https://doi.org/10.62159/jpi.v6i2.2249>
- Rao, M. J., Wang, H., & Lei, H. (2024). LC-MS/MS-based metabolomic study provides insights into altitude-dependent variations in flavonoid profiles of strawberries. *Frontiers in Plant Science*, 15, Article 1527212. <https://doi.org/10.3389/fpls.2024.1527212>
- Rodrigues, J. F., Soares, C., Moreira, M. M., Ramalhosa, M. J., Duarte, N. F., Delerue-Matos, C., & Grosso, C. (2023). *Moringa oleifera* Lam. commercial beverages: A multifaceted investigation of consumer perceptions, sensory analysis, and bioactive properties. *Foods*, 12(11), Article 2253. <https://doi.org/10.3390/foods12112253>
- Sala, A., Porcaro, L., & Gómez, E. (2024). Social media use and adolescents' mental health and well-being: An umbrella review. *Computers in Human Behavior Reports*, 14, Article 100404. <https://doi.org/10.1016/j.chbr.2024.100404>
- Sharma, K., & Gera, M. (2025). A qualitative study of online disinhibition and parasocial bonds among Indian adolescents. *Digital Learning, Social Science, and Life-course Studies*, 1(2), 68–83. <https://doi.org/10.70211/disolife.v1i2.318>
- Stohs, S. J., & Hartman, M. J. (2015). Review of the safety and efficacy of *Moringa oleifera*. *Phytotherapy Research*, 29(6), 796–804. <https://doi.org/10.1002/ptr.5325>
- Sufian, M., Rimadhona, Kesuma, G. C., Hijriyah, U., & Erlina. (2023). Listening and vocabulary gains via Arabic song media: A two-cycle classroom study in Grade X. *JPI: Jurnal Pustaka Indonesia*, 3(1), 32–42. <https://doi.org/10.62159/jpi.v3i1.765>
- Towner, E., Grint, J., Levy, T., Blakemore, S.-J., & Tomova, L. (2022). Revealing the self in a digital world: A systematic review of adolescent online and offline self-disclosure. *Current Opinion in Psychology*, 45, Article 101309. <https://doi.org/10.1016/j.copsy.2022.101309>
- Valkenburg, P. M., Beyens, I., Pouwels, J. L., van Driel, I. I., & Keijsers, L. (2021). Social media use and adolescents' self-esteem: Heading for a person-specific media effects paradigm. *Journal of Communication*, 71(1), 56–78. <https://doi.org/10.1093/joc/jqaa039>
- Vergara-Jimenez, M., Almatrafi, M., & Fernandez, M. L. (2017). Bioactive components in *Moringa oleifera* leaves protect against chronic disease. *Antioxidants*, 6(4), Article 91. <https://doi.org/10.3390/antiox6040091>
- von Gillern, S., Korona, M., Wright, W., Gould, H., & Haskey-Valerius, B. (2024). Media literacy, digital citizenship and their relationship: Perspectives of preservice teachers. *Teaching and Teacher Education*, 138, Article 104404. <https://doi.org/10.1016/j.tate.2023.104404>
- Züst, T., & Agrawal, A. A. (2017). Trade-offs between plant growth and defense against insect herbivory: An emerging mechanistic synthesis. *Annual Review of Plant Biology*, 68(1), 513–534. <https://doi.org/10.1146/annurev-arplant-042916-040856>