



Comparative Study of the Nutritional, Phytochemical Composition and Antioxidant Potential of Soybean [*Glycine max* (L.) Merrill] from Burkina Faso

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ABSTRACT

Background: The soybean crop plays a crucial role in Burkina Faso's agricultural sector and contributes significantly to food security and nutrition. The study aimed to evaluate the nutritional composition and antioxidant potential of soybean cultivated in Burkina Faso.

Methods: A total of 40 soybean varieties cultivated in 2022 at two sites in Burkina Faso were analyzed using standard methods for six parameters, including total phenolic, total flavonoid, total protein, soluble sugars, phytic acid, DPPH radical scavenging activity and ferric reducing antioxidant power (FRAP). Total phenolic ranged from 1.769 to 2.923 µg GAE/100 mg, total flavonoid from 0.008 to 0.031 µg QE/100 mg, total protein from 1.526 to 2.021 mg/100 mg, soluble sugar from 107.6 to 228.1 µg GE/100 mg and phytic acid concentration from 130.9 to 378.0 µg APE/100 mg. Antioxidant activity varied from 0.786 to 2.282 µg AAE/100 mg for DPPH and from 0.019 to 0.079 µg AAE/100 mg dw for FRAP.

Result: Four soybean varieties, GPV12, GPV17, GPV22 and GMV19 are characterized by high nutrient content, particularly total protein and soluble sugars. The GPV3, GPV6 and GPV8 lines are distinguished by their high concentration of bioactive compounds, such as total phenolic compounds and total flavonoids. In contrast, the GPV4 and GPV5 varieties have relatively high levels of antinutrients. The varieties with high nutritional potential could help strengthen the resilience of poor households against food insecurity in Sub-Saharan Africa.

Key words: Burkina faso, *Glycine max*, Nutrients, Phytochemicals compounds.

INTRODUCTION

Soybean [*Glycine max* (L.) Merrill] is a legume widely consumed worldwide due to its high nutritional value and health benefits (Amol *et al.*, 2021). In terms of protein, the nutritional value of soybean amino acids is significantly higher than that of most legumes (Messina, 2022). The seed is an excellent source of essential nutrients, providing proteins, essential amino acids, oil, carbohydrates, dietary fiber, vitamins and minerals for both human and animal nutrition (Alghafis and Raouf, 2020). Moreover, soybean, as a nitrogen-fixing legume, helps reduce the use of chemical sources for nitrogen fertilizer production (Patil *et al.*, 2024). However, the relatively low genetic variation among soybean cultivars limits the improvement of these nutritional characteristics. Determining the phytochemical diversity of soybean cultivars is of utmost importance (Azam *et al.*, 2021). This will help breeders to develop new cultivars with enhanced nutrition and expand the genetic diversity of soybean cultivars (Singer *et al.*, 2023). The nutritional and phytochemical characteristics of soybean are mainly influenced by various factors such as genotype, location, climate, water availability and maturity group (Jiang *et al.*, 2018). Multi-location trials are necessary for the effective selection of different genotypes with higher levels of desirable nutritional traits (Azam *et al.*, 2021). The present study was conducted to identify the variability of total

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phenolic, total flavonoid, total protein, soluble sugars, phytic acid, 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical

scavenging activity and ferric reducing antioxidant power (FRAP) in Burkina Faso' soybean genotype.

MATERIALS AND METHODS

Plant material

This research was conducted in 2024 at the Laboratory of Biochemistry and Chemistry Applied (LaBioCa), University Joseph Ki-Zerbo, Burkina Faso. The study material (40) consisted of 37 soybean lines (Table 1) developed by the International Institute of Tropical Agriculture (IITA) and 3 soybean lines from the Institute of Environment and Agricultural Research (INERA). The seeds used were harvested from plants at full maturity in two different agroecological zones of Burkina Faso: the northern Sudanian zone (Gampela: 12°15' North latitude, 1°12' West longitude) and the southern Sudanian zone (Farako-Ba: 11°12'0" North latitude, 4°18'0" West longitude).

Determination of nutrients and antinutrients contents

Total protein content

Total protein content was evaluated at 595 nm by using the methods of Bradford (1976). The means of three values were obtained, expressed as mg/100 mg dw.

Soluble sugar content

Total soluble sugars was evaluated using the phenol-acid sulfuric method of DuBois *et al.* (1956) and the absorbance was read at 490 nm. The total sugar content was expressed as µg GE/100 mg dw.

Phytic acid content

Phytic acid content (PAC) was determined using the method of Latta and Eskin (1980). The PAC was determined using phytic acid as the standard and expressed in µg APE/100 mg dw.

Bioactive compounds quantification

Extraction method of bioactive compounds

The dried soybean seeds were ground. Seeds powders (0.5 g each) from different soybean varieties were extracted with 10 mL of ethanol 80% (v/v). The mixture was shaken for 24 h and centrifuged at 4500 rpm for 10 minutes. The supernatant was used for the quantification of total phenolics, total flavonoids, DPPH and FRAP.

Total phenolic content

Total phenolic content of the soybean seed extracts was determined at 760 nm according to the method described by Singleton *et al.* (1999), using gallic acid as a standard. Total phenolic was expressed in µg of gallic acid equivalent per 100 g of dry weight.

Total flavonoid content

The total flavonoid content of the soybean seed extracts was determined at 415 nm using the method described by Arvouet-Grand *et al.* (1994). The total flavonoid content was determined on a quercetin calibration curve and

expressed as µg of quercetin equivalents (QE) per 100 mg of dry seed weight.

DPPH radical scavenging activity

The ability of soybean seed extracts to scavenge the DPPH radical was evaluated at 517 nm as described by Sombié *et al.* (2011). The means of three values were obtained, expressed as µg of ascorbic acid equivalent per 100 g of dry seeds weight (µg AAE/100 mg dw).

Ferric reducing antioxidant power (FRAP) assay

The ability of the cowpea seed extracts to reduce iron (III) to iron (II) was measured at 700 nm following the procedure

Table 1: List of soybean lines used in this study.

Code gen	Lines	Origin
GMV1	TGX2025-6E	IITA
GMV2	TGX2009-16F	IITA
GMV3	TGX2017-5E	IITA
GMV5	TGX2016-3E	IITA
GMV6	TGX2011-6F	IITA
GMV7	TGX1987-14F	IITA
GMV8	TGX2017-6E	IITA
GMV9	TGX2025-10E	IITA
GMV10	TGX2015-1E	IITA
GMV11	TGX2025-14E	IITA
GMV12	TGX2008-4F	IITA
GMV13	TGX1989-19F	IITA
GMV15	TGX1993-4FN	IITA
GMV16	TGX2010-11F	IITA
GMV17	TGX2020-1E	IITA
GMV18	TGX2019-1E	IITA
GMV19	TGX2016-4E	IITA
GMV20	TGX2027-1E	IITA
GMV21	TGX2023-3E	IITA
GPV3	TGX2010-14F	IITA
GPV4	TGX1835-10E	IITA
GPV5	TGX2027-4E	IITA
GPV6	TGX1988-5F	IITA
GPV7	TGX2023-4E	IITA
GPV8	TGX1987-10F	IITA
GPV9	TGX1951-4F	IITA
GPV10	TGX2025-16E	IITA
GPV11	TGX2027-7E	IITA
GPV12	TGX2004-7F	IITA
GPV13	TGX2009-1F	IITA
GPV14	TGX2023-1E	IITA
GPV17	TGX2010-5F	IITA
GPV19	TGX2007-3F	IITA
GPV20	TGX2018-5E	IITA
GPV21	TGX2013-2F	IITA
GPV22	TGX2007-1F	IITA
G175 (check 1)	TGM249-4-6	INERA
G196 (check 2)	SCHV456	INERA
G197 (check 3)	SCHV457	INERA

described by Hinneburg *et al.* (2006). Iron (III) reducing activity was determined as μg of ascorbic acid equivalent (AAE) per 100 mg of dry seed weight ($\mu\text{g AAE}/100 \text{ mg dw}$).

Statistical analysis

Before analyzing variance (ANOVA), the assumptions of normality and homoscedasticity were verified using the Shapiro-Wilk and Levene's tests, respectively. An analysis of variance was performed to estimate the effects of genotype, environment and genotype $\times$ environment (G $\times$ E) interaction on the measured traits at the 1% threshold level. Analysis of variance across the two sites was conducted for each trait and the LSD (least significant difference) test was applied to identify groups of genotypes that actually differ from each other. Pearson's correlation test was used to determine the relation between phenolic content, flavonoid content and antioxidant activities using the R software package (version 4.4.0).

RESULTS AND DISCUSSION

Variation in nutrient and antinutrient contents, bioactive compounds and antioxidant activity

Soybean is an important but underutilized legume contributing to food and nutritional security in Burkina Faso. This study evaluated variation in nutrient, antinutrient, phytochemical composition and antioxidant activity among 40 soybean genotypes grown under two contrasting environments. Analysis of variance revealed highly significant effects ($p \leq 0.001$) of genotype (G), environment (E) and genotype $\times$ environment (G $\times$ E) interaction for all traits (Table 2). Genotype explained the largest proportion of total variation for most traits, notably total phenolic content (57.59%), soluble sugars (63.17%), FRAP (58.35%) and phytic acid content (75.04%), consistent with previous reports (Njoroge and Oyoo, 2020; Wan, 2023). In contrast, total flavonoid content, total protein and DPPH activity were more strongly influenced by G $\times$ E interaction, indicating differential genotype responses across environments, as also reported by Hailemariam (2022).

Significant genetic variability was observed among genotypes for all studied traits (Table 3). Total flavonoid

content ranged from 0.008 to 0.031 $\mu\text{g QE}/100 \text{ mg}$, while total phenolic content exceeded the grand mean (2.233 $\mu\text{g GAE}/100 \text{ mg}$) in 55% of the genotypes. Genotypes GPV3 and GPV8 exhibited high phenolic content and strong antioxidant activity (DPPH), confirming the close association between phenolics and antioxidant capacity. Similar environment-dependent variability in phytochemical composition has been attributed to biochemical regulation of antioxidant enzymes and phenolic biosynthesis in response to growing conditions (Kokebie *et al.*, 2024).

Performance of the genotypes in each environment

Genotype performance varied markedly between environments (Fig 1). Farako-Ba, characterized by higher rainfall, generally promoted greater accumulation of nutritional and antioxidant compounds compared with the drier Gampela site, in agreement with earlier findings on the influence of climatic conditions on phenolic content and antioxidant capacity (Tolic *et al.*, 2017). Several genotypes exhibited high levels of phytic acid and soluble sugars, traits of functional and nutritional interest. Although phytic acid is considered an antinutrient due to mineral chelation (Lott *et al.*, 2000), its antioxidant and anticancer properties have been widely documented (Vucenik and Shamsuddin, 2006). Similarly, soluble sugars play a key role in glycemic regulation and intestinal health (Fu *et al.*, 2022), with marked genetic variability previously reported in tropical soybean environments (Jiang *et al.* (2018). Overall, the wide genetic diversity observed for nutritional, phytochemical and antioxidant traits highlights the importance of genotype selection and environment-specific breeding strategies for improving soybean nutritional quality and sustainability in sub-Saharan Africa.

Relationship between antioxidant activity and the studied traits

To identify the phytochemical compounds likely contributing to the antioxidant activity of soybeans, Pearson's correlation coefficient was calculated (Table 4). Total phenolic content is positively correlated with DPPH ($r = 0.519$) and FRAP ($r = 0.304$). The antioxidant activities show a strong positive correlation with each other ($r = 0.508$). However, no

Table 2: Combined analysis of variance for 7 traits and the percentage of mean squares for genotype (G), environment (E) and genotype $\times$ environment interaction (G $\times$ E).

SV	df	TFC	TPC	PrT	SS	PAC	DPPH	FRAP
E	1	0.000*	2.569***	0.487***	8334***	102487***	14.560***	0.003***
G	39	0.004***	11.606***	3.498***	249528***	947510***	43.800***	0.059***
GEI	39	0.005***	5.248***	5.791***	128234***	995968***	14.520***	0.015***
% E	1	0.20	12.75	4.79	2.10	4.97	21.17	4.55
% G	39	40.42	57.59	34.42	63.17	45.96	58.35	75.04
% G $\times$ E	39	49.04	26.04	56.97	32.45	48.30	20.11	19.71
Resid	160	10.18	3.62	3.82	2.28	0.77	0.37	0.70

SV= Source of variation; E= Environment; G= Genotype; GEI= Genotype by environment interaction; TFC= Total flavonoids content ($\mu\text{g QE}/100 \text{ mg}$); TPC= Total phenolic content ($\mu\text{g GAE}/100 \text{ mg}$); PrT= Total protein (mg/100 mg); SS= Soluble sugars ($\mu\text{g GE}/100 \text{ mg}$); DPPH ($\mu\text{g AAE}/100 \text{ mg}$); FRAP ($\mu\text{g AAE}/100 \text{ mg}$); PAC= Phytic acid content ($\mu\text{g APE}/100 \text{ mg}$).

significant relationship was found between the antioxidant activity and total flavonoids content. Similar results were reported by Priastomo *et al.* (2024). The total protein content is negatively correlated with FRAP ($r = -0.237$). Similarly, the phytate content is negatively and weakly correlated with FRAP ($r = -0.164$). The positive correlation between DPPH, FRAP and total phenolic content in soybean seeds indicates

that higher phenolic levels enhance antioxidant activity. This finding is consistent with a previous study that reported that the phenolic compounds are responsible for the level of antioxidant activity (Arifin *et al.*, 2021). Studies show that as total phenolic content increases, both DPPH scavenging and FRAP values improve, reflecting a synergistic relationship where phenolics contribute significantly to the

Table 3: Mean values of soybean phytochemical traits of 40 genotypes evaluated at gampela and farako-Ba, burkina faso, during the 2022 growing season.

Code gen	TFC	TPC	PrT	SS	PAC	DPPPH	FRAP
G196	0.025 ^{ab}	2.147 ^c	1.957 ^{a-c}	209.509 ^{a-d}	254,863 ^{a-g}	1.541 ^{a-h}	0.034 ^{h-k}
G197	0.031 ^a	2.450 ^{bc}	1.94 ^{a-c}	170.320 ^{b-i}	308,392 ^{a-f}	1.561 ^{a-h}	0.032 ^{h-k}
G175	0.024 ^{a-c}	1.866 ^{e-g}	1.833 ^{a-d}	186.40 ^{a-h}	199,765 ^{c-g}	1.541 ^{a-h}	0.019 ^k
GPV4	0.012 ^{b-e}	2.297 ^{b-e}	1.802 ^{a-d}	155.951 ^{d-j}	378,000 ^a	1.304 ^{d-h}	0.046 ^{e-i}
GPV9	0.014 ^{b-e}	2.209 ^{c-f}	1.708 ^{a-d}	215.680 ^{a-c}	227,412 ^{a-g}	2.124 ^{a-d}	0.072 ^{a-c}
GPV8	0.016 ^{b-e}	2.662 ^b	1.830 ^{a-d}	149.419 ^{e-j}	242,510 ^{a-g}	2.282 ^a	0.060 ^{a-f}
GMV7	0.016 ^{b-e}	2.134 ^{c-g}	1.807 ^{a-d}	150.860 ^{e-j}	228,588 ^{a-g}	1.594 ^{a-g}	0.043 ^{f-j}
GPV6	0.022 ^{b-d}	2.120 ^{c-g}	1.757 ^{a-d}	121.536 ^{ij}	168,000 ^{e-g}	1.899 ^{a-f}	0.044 ^{f-j}
GMV13	0.020 ^{b-e}	2.307 ^{b-d}	1.928 ^{a-c}	190.996 ^{a-g}	213,882 ^{a-g}	1.614 ^{a-g}	0.048 ^{e-i}
GMV15	0.013 ^{b-e}	2.288 ^{b-e}	1.955 ^{a-c}	163.698 ^{c-d-i}	266,824 ^{a-g}	2.138 ^{a-d}	0.079 ^a
GPV12	0.013 ^{b-e}	2.245 ^{b-e}	1.961 ^{a-c}	198.473 ^{a-f}	276,628 ^{a-g}	1.158 ^{f-h}	0.032 ^{h-k}
GPV22	0.013 ^{b-e}	1.835 ^{fg}	1.813 ^{a-d}	228.113 ^a	238,980 ^{a-g}	0.987 ^{gh}	0.031 ^{h-k}
GPV19	0.012 ^{b-e}	2.247 ^{b-f}	1.608 ^{b-d}	188.248 ^{a-h}	325,255 ^{a-e}	1.341 ^{d-h}	0.034 ^{h-k}
GMV12	0.018 ^{b-e}	2.336 ^{b-d}	1.896 ^{a-d}	149.824 ^{e-j}	265,059 ^{a-g}	1.843 ^{a-f}	0.050 ^{e-h}
GMV2	0.016 ^{b-e}	2.445 ^{bc}	1.828 ^{a-d}	109.824 ^l	205,843 ^{a-g}	1.441 ^{a-h}	0.029 ^{i-k}
GPV13	0.014 ^{b-e}	2.198 ^{c-f}	1.720 ^{a-d}	206.221 ^{a-e}	240,353 ^{a-g}	2.114 ^{a-d}	0.050 ^{e-h}
GPV1	0.021 ^{b-d}	2.383 ^{b-d}	1.954 ^{a-c}	121.716 ^{ij}	276,235 ^{a-g}	2.013 ^{a-e}	0.050 ^{d-h}
GMV16	0.014 ^{b-e}	2.169 ^{c-g}	1.957 ^{a-c}	176.581 ^{a-i}	349,373 ^g	0.875 ^{gh}	0.031 ^{h-k}
GPV3	0.022 ^{b-d}	2.923 ^a	1.851 ^{a-d}	167.572 ^{b-i}	264,078 ^{a-d}	2.226 ^{ab}	0.076 ^{ab}
GPV17	0.015 ^{b-e}	1.769 ^g	2.021 ^a	185.725 ^{a-h}	285,843 ^{a-g}	1.252 ^{e-h}	0.025 ^{jk}
GMV6	0.016 ^{b-e}	2.346 ^{b-d}	1.955 ^{a-c}	165.410 ^{c-i}	189,961 ^{a-g}	2.043 ^{a-e}	0.065 ^{a-e}
GPV21	0.015 ^{b-e}	2.442 ^{bc}	1.612 ^{a-d}	204.419 ^{a-e}	169,569 ^{c-g}	2.226 ^{ab}	0.061 ^{a-f}
GMV10	0.014 ^{b-e}	2.265 ^{b-f}	1.860 ^{a-d}	214.014 ^{a-c}	145,647 ^{e-g}	2.003 ^{a-e}	0.064 ^{a-e}
GMV5	0.015 ^{b-e}	2.410 ^{bc}	1.964 ^{ab}	222.887 ^{ab}	254,471 ^{fg}	2.218 ^{ab}	0.064 ^{a-e}
GMV19	0.015 ^{b-e}	2.274 ^{b-e}	1.742 ^{a-d}	204.964 ^{a-e}	282,314 ^{a-g}	1.244 ^{e-h}	0.031 ^{h-k}
GMV3	0.014 ^{b-e}	2.243 ^{b-f}	1.811 ^{a-d}	195.725 ^{a-f}	182,706 ^{a-g}	1.618 ^{a-g}	0.055 ^{c-g}
GMV8	0.018 ^{b-e}	2.250 ^{-f}	1.844 ^{a-d}	217.482 ^{a-c}	130,941 ^{d-g}	1.375 ^{c-h}	0.051 ^{c-g}
GPV20	0.017 ^{b-e}	2.468 ^{bc}	1.551 ^{cd}	132.347 ^{h-j}	200,745 ^g	1.411 ^{b-h}	0.056 ^{c-g}
GMV18	0.011 ^{c-e}	2.045 ^{-g}	1.875 ^{a-d}	135.951 ^{g-j}	328,784 ^{c-g}	0.861 ^{gh}	0.036 ^{g-k}
GMV17	0.010 ^{de}	1.941 ^{d-g}	1.836 ^{a-d}	143.969 ^{f-j}	222,902 ^{a-e}	2.061 ^{a-e}	0.066 ^{a-e}
GPV14	0.014 ^{b-e}	2.196 ^{c-f}	1.603 ^{b-d}	189.104 ^{a-h}	146,824 ^{a-g}	2.206 ^{a-c}	0.061 ^{a-f}
GMV21	0.018 ^{b-e}	2.314 ^{b-d}	1.774 ^{a-d}	214.824 ^{a-c}	269,569 ^{fg}	2.110 ^{a-d}	0.070 ^{a-d}
GPV7	0.008 ^e	1.833 ^{fg}	1.772 ^{a-d}	107.572 ^l	368,196 ^{a-g}	1.361 ^{d-h}	0.025 ^{jk}
GMV9	0.017 ^{b-e}	1.937 ^{d-g}	1.877 ^{a-d}	163.293 ^{c-i}	249,961 ^{ab}	0.786 ^h	0.038 ^{g-j}
GMV11	0.020 ^{b-e}	2.093 ^{c-g}	1.913 ^{a-d}	135.410 ^{g-j}	314,863 ^{a-g}	1.652 ^{a-g}	0.048 ^{e-i}
GPV10	0.011 ^{c-e}	2.381 ^{b-d}	1.861 ^{a-d}	174.914 ^{a-i}	206,628 ^{a-e}	1.545 ^{a-g}	0.042 ^{f-j}
GMV1	0.016 ^{b-e}	2.191 ^{c-f}	1.977 ^{ab}	173.698 ^{a-i}	354,353 ^{b-g}	1.963 ^{a-f}	0.059 ^{b-f}
GMV20	0.016 ^{b-e}	2.214 ^{c-f}	1.813 ^{a-d}	152.257 ^{e-j}	312,706 ^{a-c}	2.003 ^{a-e}	0.070 ^{a-d}
GPV5	0.014 ^{b-e}	2.096 ^{c-g}	1.786 ^{a-d}	149.104 ^{e-j}	318,980 ^{a-e}	1.365 ^{d-h}	0.029 ^{i-k}
GPV11	0.013 ^{b-e}	2.330 ^{b-d}	1.526 ^d	180.996 ^{a-h}	324,667 ^{a-e}	1.899 ^{a-f}	0.040 ^{g-j}
Mean	0.016	2.233	1.827	173.125	254.766	1.669	0.048
C.V (%)	0.424	0.130	0.112	0.234	0.364	0.331	0.380
LSD _{0.05}	0.006	0.235	0.208	30.715	84.981	0.444	0.011

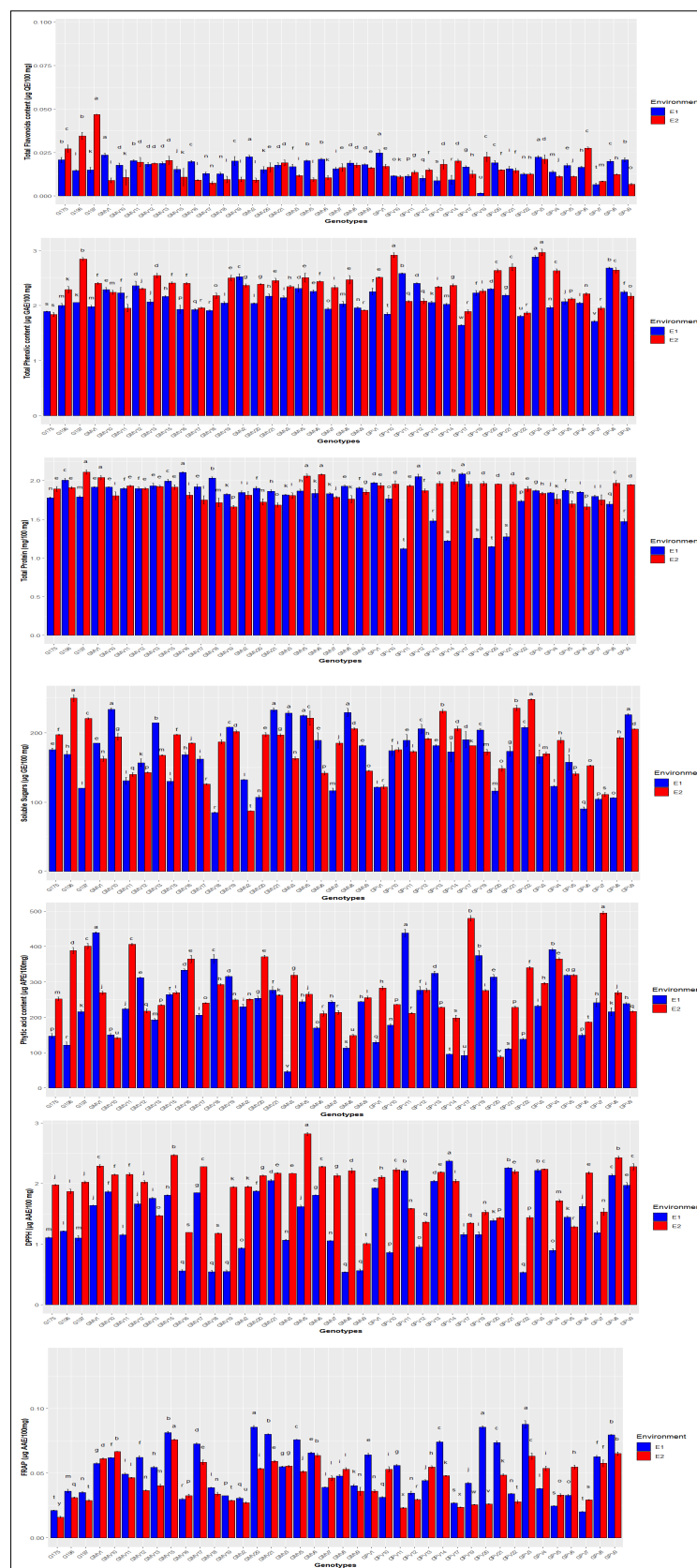


Fig 1: Biochemical compound content of soybean varieties grown at gampela (E1) and farako-Ba (E2), Burkina faso, during the 2022 growing season.

Table 4: Pearson’s correlation coefficient.

Variable	TFC	TPC	PrT	SS	DPPH	FRAP	PAC
TFC	1						
TPC	0.165*	1					
PrT	0.216***	0.006	1				
SS	0.157*	0.138*	0.034	1			
DPPH	0.015	0.519***	-0.094	0.130*	1		
FRAP	-0.017	0.304***	-0.237***	0.068	0.508***	1	
PAC	-0.001	0.054	-0.046	-0.058	-0.015	-0.164*	1

* $p < 0.05$; ** $p < 0.01$ and *** $p < 0.$

Table 5: Eigenvalues and proportion of the variance explained for the three principal components of the 40 soybean genotypes based on phytochemical components.

Variables	Dim.1	Dim.2	Dim.3
Eigen values	2.44	1.30	1.12
% of variance	34.85	18.62	16.12
Cumulative % of variance	34.85	53.47	69.60
TFC	0.22	0.83	-0.12
TPC	0.70	0.18	0.34
PrT	-0.19	0.73	-0.03
SS	0.22	-0.12	-0.80
DPPH	0.87	-0.04	0.15
FRAP	0.85	-0.14	0.14
PAC	-0.54	-0.02	0.54

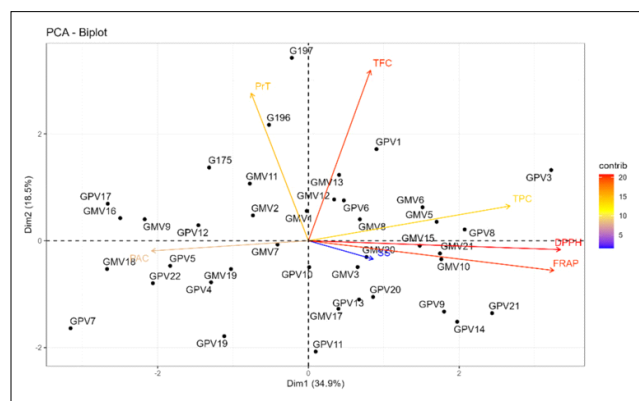


Fig 2: PCA showing the spatial distribution of 40 soybean genotypes based on their Nutritional, phytochemical and antioxidant characteristics.

overall antioxidant capacity of soybean seeds (Alsuwayt, 2025). Flavonoids present in soybeans play a crucial role in improving protein quality (Oliveira *et al.*, 2024). They can enhance protein digestibility and nutritional value by acting as antioxidants, which protect amino acids from oxidative damage (Prodić *et al.*, 2023). By incorporating flavonoids into the diet, it is possible to potentially improve the overall quality of soybean proteins (Jia *et al.*, 2022).

Association between nutritional and phytochemical contents

The first three principal components explained 69.60% of the total variance (Table 5; Fig 2), indicating a substantial

representation of the biochemical diversity among soybean genotypes. The first principal component (Dim.1; eigenvalue = 2.44) accounted for 34.85% of the total variance and was strongly associated with antioxidant activities (DPPH, FRAP) and total phenolic content, reflecting the bioactive potential of the genotypes. Genotypes positioned in the positive quadrant of Dim.1 exhibited high antioxidant capacity and phenolic content and are therefore of interest for nutraceutical and functional applications. In this regard, GMV21, GPV20, GPV3, GPV8 and GMV20 displayed the greatest variability and represent promising candidates. The second principal component (Dim.2; eigenvalue = 1.30), explaining 18.62% of the total variance, was mainly influenced by total flavonoid and protein contents, indicating a nutritional and functional dimension. Genotypes located in the positive quadrant of Dim.2 combined high flavonoid and protein levels, making them suitable for breeding programs targeting both nutritional quality and health benefits. The most variable genotypes along this axis were GPV5, GPV12, GMV18, GMV16 and GMV9. The third principal component (Dim.3; eigenvalue = 1.12) explained an additional 16.12% of the total variance and was characterized by strong contributions from soluble sugars and phytic acid, highlighting variability related to carbohydrate content and specific antinutritional compounds. Genotypes GMV13, GMV12, GMV7, GMV11 and GPV1 showed the highest variability along this component. While genotypes located in the negative quadrants of Dim.1 and/or Dim.2 exhibited lower antioxidant or functional compound contents, some displayed high soluble sugar or tannin levels, indicating alternative valorization pathways.

Globally, several genotypes (GMV5, GMV15, GMV21 and GPV8) showed positive loadings in at least two principal components, demonstrating their potential for targeted phytochemical improvement. The wide dispersion of genotypes confirms high biochemical diversity within the collection, allowing effective discrimination based on antioxidant, nutritional and phytochemical attributes and providing a robust basis for selection in breeding and utilization programs.

Cluster and heatmap analysis

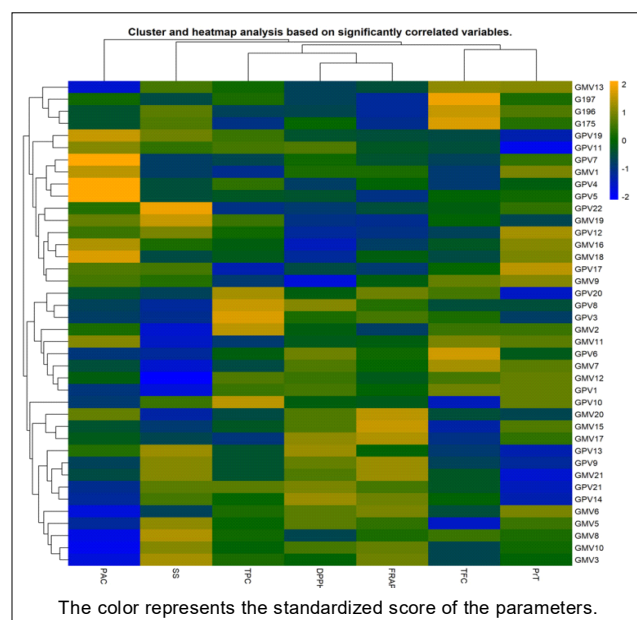
A combined cluster and heatmap analysis were conducted to assess the variability among soybean genotypes concerning the total flavonoid content, total phenolic content,

Table 6: Average cluster values of nutritional components, phytochemicals and antioxidant activities of 40 soybean genotypes.

Cluster	Number of genotypes	TFC	TPC	PrT	SS	DPPH	FRAP	PAC
1	12	0.013 ^b	2.089 ^b	1.811 ^a	172.914 ^a	1.203 ^c	0.033 ^b	310.582 ^a
2	11	0.015 ^b	2.243 ^{ab}	1.880 ^a	156.482 ^a	1.658 ^b	0.039 ^b	236.930 ^b
3	17	0.020 ^a	2.327 ^a	1.803 ^a	184.043 ^a	2.007 ^a	0.063 ^a	226.909 ^b

Table 7: Composition and characteristics of the different groups.

Group	Genotypes	Characteristics
1	GPV22, GMV16, GPV12 GPV17, GMV9, GMV19, GPV19, GPV11, GPV7, GPV4, GMV18, GPV5	High values for PAC, low values for DPPH, FRAP, PT and FTC
2	GPV6, GPV1, GMV7, GPV10, GMV2, GMV11, GMV12, G197, G175, G196, GMV13	High values for FTC
3	GPV20, GPV14, GPV21, GMV8, GMV3, GMV10, GMV5, GMV21, GPV13, GPV9, GPV8, GPV3, GMV17, GMV1, GMV6, GMV20, GMV15	High values for FRAP, DPPH and PTC

**Fig 3:** Cluster and heatmap analysis based on significantly correlated variables.

total protein, soluble sugars, phytic acid content and antioxidant activity. All genotypes were divided into three main groups (Table 6 and 7). In particular, Fig 3 shows the cluster analysis according to the average linkage method. Cluster 1 included only three varieties (GPV5, GPV4 and GPV7), which have high values in phytic acid content and low content in bioactive compounds (DPPH, FRAP, TPC, TFC). Cluster 2 also contained only two varieties (GPV6, GMV7) that have the highest total flavonoid content and total proteins. Cluster 2 is intermediate in antioxidant compounds and total flavonoids. Cluster 3 consisted of three varieties (GPV3, GPV8 and GPV20), which are prominent in the total phenol content and antioxidant activity. This cluster is rich in flavonoids and polyphenols and has high antioxidant activity (DPPH, FRAP), but low phytic acid content.

CONCLUSION AND PERSPECTIVES

In this study, for all the traits analyzed, genetic variation was primarily influenced by genotype, followed by the effects of the environment and the genotype × environment interaction (GEI). The Gampela locality was found to be less productive in terms of nutritional compounds, phytochemicals and antioxidant activities, whereas Farako-Ba was more productive. The variability among soybean varieties was also described through cluster analysis, which divided them into three groups. Moreover, correlation analysis indicated that total phenolic content was correlated with antioxidant activities. These results could contribute to the improvement of soybean breeding programs through an approach based on nutritional, phytochemical and antioxidant criteria. The soybean lines GPV12, GPV17, GPV22 and GMV19 are characterized by high nutrient content, particularly total protein and soluble sugars. The GPV3, GPV6 and GPV8 lines are distinguished by their high concentration of bioactive compounds, such as total phenolic compounds and total flavonoids. In contrast, the GPV4 and GPV5 lines have relatively high levels of antinutrients. Furthermore, this study makes a significant contribution to the mapping of Burkina Faso's plant genetic resources.

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Conflict of interest

The authors have declared that no conflict of interest exists.

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