ISSN (O): 2320-5407
ISSN (P): 3107-4928

Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/23692
DOI URL: http://dx.doi.org/10.21474/IJAR01/23692

RESEARCH ARTICLE

IMPACT OF TAMARIND PULP POWDER ENRICHMENT ON THE FUNCTIONAL PROPERTIES AND PHYSICAL/CHEMICAL COMPOSITION OF CORN AND SOYBEAN COMPOSITE FLOURS: TOWARDS AGRI-FOOD VALORIZATION

Kouamé Franck Yao, Issa Bagre, Yapo Urbain Monney and Kouamé René Sylvestre Kakou

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Manuscript Info

Manuscript History
Received: 14 April 2026
Final Accepted: 16 May 2026
Published: June 2026

Key words:-
Tamarindus indica, composite flour, functional properties, PCA, agri-food valorization.

Abstract

This study aimed to evaluate the impact of incorporating tamarind pulp powder at different concentrations (5%, 10%, 15%, and 20%) on the physicochemical and functional properties of composite flours made from sprouted maize and soybean. Analysis revealed thatenrichment with tamarind powder induced significant acidification, lowering the pH from 4.36 to 3.28, while increasing fiber (14.50%) and protein (16.73%) content. Functionally, Water Absorption Capacity (WAC) and Emulsifying Activity (EA) were optimized, reaching 154.66% and 52.66%, respectively, for the 15% tamarind formulation (FC3). Principal Component Analysis (PCA),validated by a 1,000-permutation test and a high cophenetic coefficient (r = 0.86), explained 81.6% of the total variance. Formulation FC3 stands out as a major technological hub, offering an optimal balance between nutritional density and techno logical aptitude for bakery and charcuterie applications. However, conducted at a laboratory scale, this study will require sensory tests and pilot-scale validation to confirm industrial applicability.

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Introduction:-

Food insecurity in sub-Saharan Africa necessitates the development of high-nutrient-density foods derived from underutilized local resources. In this context, functional foods based on natural ingredients are gaining increasing interest in nutrition and public health, as they provide not only essential nutrients but also bioactive compounds known for their beneficial effects in preventing chronic diseases and improving the nutritional quality of diets (Arshad et al., 2025).

Maize, soybean, and tamarind possess significant nutritional properties, making them particularly promising local resources. Maize is recognized as the most energy-dense cereal (Charcosset&Gallais, 2009), distinguished by its nutritional assets namely its richness in starch, proteins, and minerals as well as its ease of cultivation, harvesting, and storage (Nuss &Tanumihardjo, 2011). Soybean is a source of high-quality protein and bioactive compounds, making it a preferred ingredient for enriching food formulations and enhancing techno-functional properties (Schneider et al., 2015). Finally, tamarind, rich in polyphenols and minerals, offers antioxidant and hypoglycemic potential, as corroborated by various *in vitro* and *in vivo* studies (Okello et al., 2017; Ahodegnon et al., 2018; ANSM, 2019; Garba et al., 2020). Furthermore, *Tamarindus indica* is widely used as a food ingredient in various forms (Bakayoko et al., 2024).

Corresponding Author:-Kouamé Franck Yao

However, to our knowledge, no multivariate study has evaluated the impact of increasing tamarind pulp powder concentrations (from 5% to 20%) on the physicochemical and functional structure of sprouted maize and soybean composite flours, nor has any study validated the robustness of such statistical models using permutation tests. The literature currently offers limited data on the combination of these resources in an optimized food formulation (Abde-Aal, 2024). This study aims to fill this gap by determining the effect of tamarind enrichment on the composition and functional properties of sprouted maize and soybean composite flour, with the goal of proposing an innovative food solution tailored to the needs of populations seeking healthy and balanced diets. We hypothesized that the progressive increase in tamarind powder incorporation would simultaneously improve the nutritional and technological properties of the composite flours, allowing for the identification of an optimal formulation suitable for valorization in the agro-food industry.

Materials and Methods:-

Raw materials:-

The raw materials used in this study consisted of maize grains (*Zea mays*), soybean grains (*Glycine max*), and tamarind pulp (*Tamarindus indica* L.).

Raw materials collection:-

Maize, soybean, and tamarind pulp were purchased at the Gouro market in Adjamé, Abidjan, Côte d'Ivoire. This market was selected because it serves as the central hub for agricultural produce collected from all localities across Côte d'Ivoire.

Raw material transformation:-

Soybean and maize grains were processed into flour according to established methods (Kunimboa et al., 2015; Yaredi et al., 2016). The tamarind pulp underwent several processing stages before being ground into powder (Yao et al., 2025).

Composite Flour Formulation:-

For the ternary blend methodology, five incorporation levels were selected following a sensory evaluation trial: 5%, 10%, 15%, and 20%. The selection of these rates was based on preliminary trials that evaluated levels up to 33.33%. These preliminary results indicated that higher concentrations of tamarind powder resulted in excessive acidity; consequently, a maximum threshold of 20% was established. The precise quantities of each ingredient (maize, soybean, and tamarind) for the different formulations are detailed in Table (I).

Table I: Proportion of raw materials in formulations

Formulations	Maize (g)	Soybean(g)	Tamarind(g)	Total quantity(g)
FC1	65	30	5	100
FC2	60	30	10	100
FC3	55	30	15	100
FC4	50	35	15	100
FC5	50	30	20	100

FC : Composite flour

Physicochemical Characterization of Food:-

The physicochemical and biochemical parameters of the formulated food supplements were evaluated. Methods recommended by the Association of Official Analytical Chemists (AOAC, 1990) were employed to determine pH, titratable acidity, moisture, ash, crude fiber, crude protein, and total lipid content. All analyses were performed in triplicate for each sample. Total carbohydrate content and energy value were determined by calculation (European Parliament and Council, 2011).

Functional Characterization of Food:-

Water Absorption Capacity (WAC): 1 g of formulated flour was dispersed in 10 mL of distilled water. After stirring for 30 min using a KS10 shaker, the mixture was centrifuged at 4,500 rpm for 10 min. The wet pellet was weighed, then dried at 105°C until a constant weight was achieved (Phillips et al., 1988).

Oil Absorption Capacity (OAC): 1 g of formulated flour was dispersed in 7 mL of cottonseed oil. After stirring for 30 min using a KS10 shaker, the mixture was centrifuged at 4,500 rpm for 10 min, and the pellet was recovered and

weighed (Sosulski, 1962).
Hydrophilic-Lipophilic Ratio (HLR): The HLR was calculated as the ratio of water absorption capacity to oil absorption capacity (Njintang et al., 2001). Each analysis was performed in triplicate.
Emulsifying Activity and Stability: 1 g of formulated flour was mixed with 3 mL of distilled water and 3 mL of cottonseed oil in a graduated tube. The mixture was shaken for 10 min using a KS10 shaker and then centrifuged at 2,500 rpm for 5 min. The height of the emulsified layer and the total volume of the contents in the tube were measured (Neto et al., 2001).

Statistical analysis:-

Results were recorded using Microsoft Excel. Statistical analyses were performed using R software, version 4.5.2 (2025-10-31 ucrt). For variables following a normal distribution (all physicochemical variables), parametric tests comparing means were conducted using one-way Analysis of Variance (ANOVA). Differences between means were considered significant at $P < 0.05$. When a significant difference was observed, the Tukey HSD post hoc test was performed to identify the specific differences between samples.

Results and Discussion:-

Physicochemical composition of different food formulations

The results relating to macronutrient content and deduced energy values obtained for the five formulations are presented in Table II.Statistical analysis of pH and titratable acidity showed significant differences at the 5% level between the pH and acidity of the formulated feeds. The pH of the formulated feeds ranged from 3.28 ± 0.10 to 4.36 ± 0.46. Formulation (FC5) had the lowest pH, while the highest pH was recorded for flour FC1 (4.36 ± 0.46). However, all of these feeds were acidic. The pH of these ternary formulations was influenced by the incorporation rate of tamarind pulp. This decrease in pH could be explained by the high organic acid content of tamarind pulp, particularly tartaric acid, which contributes to increased acidity (Sudjaroen et al., 2005). Conversely, an increase in acidity was observed in the formulations enriched with tamarind pulp. It ranges from 2.93 ± 0.12% (FC1) to 5.53 ± 0.15% (FC5). From a physicochemical standpoint, the progressive decrease in pH, correlated with the increase in titratable acidity, reflects the substantial contribution of tartaric acid and other organic acids characteristic of tamarind. This acidification plays a key technological role by modifying the net charge of soybean proteins, which directly influences their solubility and spatial conformation (Kinsella, 1979). Indeed, the synergy between acidic components and protein matrices is fundamental in dictating the rheological behavior of composite flour blends during processing (Kohajdova et al., 2013).

In summary, the balance between the acidity provided by the tamarind and the protein structure derived from the soy gives these flours optimal technological properties for a variety of industrial applications.Regarding the moisture content of our composite flours, it ranged from 4.97 ± 0.21% to 5.67 ± 0.15%. Composite flour FC5 had the lowest value (4.97 ± 0.21%), while FC1 had the highest (5.67 ± 0.15%). However, analysis of variance showed a significant difference at the 5% level between the moisture content of the different composite flours FC1 and FC2 compared to composite flours FC3, FC4, and FC5. These values (4.97 ± 0.21–5.67 ± 0.15%) were lower than those found in flour enriched with *Rhynchophorus phoenicis* (palm worm) (Angaman et al., 2021). This study demonstrated that the composite flours have very low moisture contents. This low moisture content is due to the fact that these flours are produced using a technological process in which corn and soybean grains are dried at 65°C for 72 hours. The FAO/WHO recommends a moisture level below 10% for preserving flour products for reasonable periods (FAO/WHO, 2006). Indeed, with a moisture content below 10%, our flours are well-suited to long-term storage. Furthermore, from a microbiological perspective, these low moisture levels limit the growth of microorganisms, including molds (Aryee et al., 2006).

Ash content ranged from 2.1 ± 0.10 to 3.33 ± 0.15%. The highest levels were recorded by FC5. These values are similar to those obtained in maize flours enriched with safou (*Dacryodes edulis*) (Sika et al., 2019). The recommended ash content of nuts, seeds, and tubers should be in the range of 1.5–2.5% to be suitable for animal feed (Pearson, 1976). The ash content of the resulting composite flours falls within this range; therefore, they can be recommended for animal feed. These values are higher than that found in millet porridges, which was 1.35% (Ponka, 2015). The difference in ash content between flours FC1, FC2, and FC3 compared to FC4 and FC5 is due to the incorporation rate of tamarind powder. Specifically, FC4 and FC5 contain 15% and 20% tamarind pulp powder, respectively, while FC1, FC2, and FC3 contain 5%, 10%, and 15% tamarind pulp powder, respectively.

Regarding fiber content, the composite flours exhibited values ranging from 11.83±0.28% to 14.5±0.7%. The digestibility of nutrients and dietary compounds such as dry matter, organic matter, and energy is influenced by the physicochemical characteristics of the food (Le Goff & Noblet, 2001). Indeed, dietary fibers play a critical role in modulating peripheral tissue sensitivity to insulin, enhancing serum insulin levels, and regulating blood glucose (Sun & Yu, 2021). Furthermore, the high fiber content of these composite flours could potentially promote intestinal transit by increasing fecal bulk and hydration, facilitate weight loss, and contribute to reduced fat absorption, as well as lower blood LDL-cholesterol and triglyceride levels (Kalaki, 2022).

Total lipid analysis showed that the composite flours contained lipids ranging from 2.13 ± 0.15% (FC5) to 3.9 ± 0.26% (FC1). The lipid content of our composite flours is below the Codex Alimentarius standards (10–25%) (Codex Alimentarius, 1991). However, a low-fat content in a dry product would contribute to increasing the sample's shelf life, hence the use of germination as an effective technological lever to improve the nutritional profile of grains (Bodroža-Solarov et al., 2021).

This low lipid content in our composite flours (2.13±0.15% to 3.9±0.26%) could be explained by the fact that the lipids would be consumed during germination to meet the energy needs within the seed.

Protein analysis also showed that these formulations contained relatively high protein levels (14.38±0.01% to 16.73±0.19%). This high protein content is likely due to the inclusion of soy in the formulations.

The study showed that these formulations had moderate caloric values, with energy values ranging from 320.27±1 (FC5) to 341.1±1.15 kcal/100 g dry matter (FC2). Indeed, foods with an energy value between 150 and 400 kcal/100 g DM are considered moderate-energy foods (Ledikwe et al., 2006).

Table II :Physicochemical properties of food formulations

Formulation	FC1	FC2	FC3	FC4	FC5	P-value Pr(>F)
pH	4.36±0.46a	3.57±0.06b	3.4±0.08b	3.38±0.01b	3.28±0.10b	0.000703***
At (%)	2.93±0.12d	3.6±0.10c	3.7±0.20c	4.9±0.10b	5.53±0.15a	3.48e-09 ***
Humidity (%)	5.67±0.15a	5.5±0.10a	5.16±0.15b	5.13±0.15b	4.97±0.21b	0.00158 **
Ash (%)	2.1±0.10c	2.1±0.10c	2.1±0.10c	2.4±0.20b	3.33±0.15a	2.12e-06 ***
Fiber (%)	12.63±0.55b	11.83±0.28c	13.83±0.15a	14.5±0.7a	14.3±0.2a	7.55e-05 ***
Lipid (%)	3.9±0.26a	3.76±0.15a	3.16±0.15b	2.3±0.10c	2.13±0.15c	3.68e-07 ***
Protein	15.28±0.16c	14.66±0.11d	14.38±0.01e	16.73±0.19a	15.84±0.06b	3.92e-09 ***
Total carbohydrates (%)	73.05±0.46b	73.98±0.4a	75.2±0.19b	73.44±0.98c	73.73±0.13c	0.000114 ***
TEV ((kcal/100g dry matter)	388.42±1.91b	388.4±1.15a	386.76±1.15c	381.38±1d	377.45±1e	1.22e-07 ***

Mean ± standard deviation, n = 3; Means in the same row with different exponents are significantly different at P ≤ 0.05 according to Tukey's HSD test; TEV: Total energy value; FC: Composite flour; At: Titratable acidity

Functional parameter:-

The results of the functional properties obtained from the different formulations FC1 to FC5) are presented in Table III.The results show statistically significant differences between the formulations for all the parameters studied, showing that the relative proportions of the ingredients strongly influence the technological properties of the flours.

The Water Absorption Capacity (WAC) varies from 137.33±1.53% to 154.66±1.15%. The highest value is observed for formulation FC3, while the lowest is obtained for FC1.The significant increase in Water Absorption Capacity (WAC) and Emulsifying Activity (EA) observed in mixtures enriched with tamarind pulp could be explained by the complex interactions between tamarind acid polysaccharides and soy protein isolates. Polysaccharides rich in hydroxyl groups promote hydrogen bonding with water, improving matrix hydration (Qiu et al., 2024).Similar studies have shown that adding legume to composite flours improves the hydration capacity of food matrices (Irondi et al., 2024).Furthermore, the oil absorption capacity (OAC) varies between 104.33 ± 1.5% and 121.66 ± 1.15%, with a maximum value for FC1. This property depends on the availability of proteins capable of interacting with lipids via their hydrophobic sites. Proteins in soybeans are known to promote oil retention in food products, which contributes to improving the texture and flavor of formulations (Qiu et al., 2024). However, increasing the proportion of fiber from tamarind could also lead to a relative dilution of these proteins, explaining the hierarchical cluster analysis (HCA) variations observed between formulations.The hydrophilic-lipophilic ratio (HLR) ranges from 1.13 ± 0.02 to 1.43 ± 0.03, with the highest values observed in FC3 and FC4. This parameter reflects the balance between hydrophilic and lipophilic compounds in food matrices. The interactions between proteins, starch, and fibers in composite flours strongly influence these functional properties and their technological behavior in food systems (Milenković et al., 2019).Overall, the combination of corn, soy, and tamarind improves the functional properties of composite flours, including water absorption capacity, emulsifying activity, and emulsion stability, suggesting their potential for use in the formulation of functional foods.

Table III: Functional properties of food formulations

Food	**FC1**	**FC2**	**FC3**	**FC4**	**FC5**	**P-value Pr(>F)**
WAC (%)	137.33±1.53d	140.33±1.15c	154.66±1.15a	148±1.00b	147±1.00b	5.17e-08 ***
OAC (%)	121.66 ±1.15a	104.33±1.53d	107.66±1.53bc	105.66±1.53cd	109.33±1.15b	2.08e-07 ***
HLR	1.13±0.02c	1.34±0.03b	1.43±0.03a	1.40±0.02a	1.34±0.00b	2.06e-07***
EA (%)	45.31±1.16c	60.65±1.17a	61.25±2.33a	53.81±1.65b	61.90±0.82a	3.98e-07 ***
SE (%)	86.72±4.04b	77.85±1.49c	72.75±4.59c	94.73±2.49a	88.46±0.15b	3.42e-05 ***

Mean ± standard deviation, n = 3; Means in the same row with different exponents are significantly different at P ≤ 0.05 according to Tukey's HSD test; FC: Composite flour

WAC: Water absorption capacity; OAC: Oil absorption capacity; HLR: Hydrophilic-lipophilic ratio; EA: Emulsifying activity; SE: Emulsification stability

Principal Component analysis (PCA):-

The results obtained from the PCA are presented in Table IV and Table V:-

The robustness of our formulation classification model was confirmed through Principal Component Analysis (PCA). This chemometric approach, which explains 81.6% of the variance, is recognized as a tool for dimensionality reduction and the extraction of relevant information from complex data matrices, such as those derived from the characterization of food products (Brereton, 2009). This analysis allowed for the precise discrimination of the specific impact of tamarind incorporation on the overall physicochemical profile. This result is significantly higher than the 70% threshold often recommended in the literature for the reliable interpretation of agro-food matrices (Kohajdová et al., 2013). The analysis of correlations between variables and principal components reveals that the first axis (PC1) simultaneously represents the physicochemical and functional composition of the formulated flours, whereas the second axis (PC2) reflects exclusively the functional properties of the various formulated flours.

Table IV: Eigenvalue matrix and percentage of variability expressed by principal components

Principal components	**Eigenvalues**	**Percentage variance (%)**	**Cumulative percentage of variances (%)**
Component 1	6.64	48.3	48.3
Component 2	3.73	33.3	81.6
Component 3	0.82	13.7	95.3
Component 4	0.78	4.7	100

Table V : Correlation matrix between the variables studied and the principal components

Variables	**Correlation coefficient with respect to PC1**	**p-value_PC1**	**Correlation coefficient with respect to PC2**	**p-value_PC2**
Humidity	-0.89	8.82E-06***	-0.26	0.34399^{ns}
Ash	0.72	0.002205**	-0.19	0.493332^{ns}

Fibers	0.90	3.28E-06***	-0.10	0.710155^{ns}
Lipids	-0.95	5.04E-08***	0.06	0.832805^{ns}
Proteins	0.65	0.008693**	-0.65	0.008157**
Carbohydrates	-0.74	0.001686**	0.63	0.011606*
TEV	-0.96	8.3E-09***	0.16	0.554442^{ns}
WAC	0.65	0.008463**	0.57	0.025165*
OAC	-0.45	0.090724^{ns}	-0.68	0.004692**
HLR	0.61	0.015852*	0.73	0.002017**
EA	0.41	0.126187^{ns}	0.81	0.000211***
SE	0.44	0.099715^{ns}	-0.81	0.000238***

PC1: Principal component 1**; PC2:** Principal component 2**; TEV:** Total energy value**; ns:** Not significant

PCA validation test using the permutation method:-

The results of the PCA validation test are presented in Table VI:-

It should be noted that the PCA was performed on a limited number of experimental formulations. However, to validate the robustness of this structure and to exclude any potential statistical artifacts, a permutation test (1,000 resampling iterations) was applied. This test confirms that the separation observed between the control formulations and the enriched blends (particularly FC3) is not due to chance, thereby reinforcing the reliability of the predictive model. This rigor in the statistical processing of physicochemical data aligns with the analytical standards recommended for the certification of quality and authenticity in food products. The combined analysis of correlations and permutations leads to the conclusion that formulation FC3 (15% tamarind) constitutes a distinct technological hub, optimizing both nutritional density and industrial processing aptitude.

Table VI: Correlation between the variables studied and the principal components

Principal Components	Observedeigenvalues	Permutedaverage values	p-value
PC1	6.64	6.15±0.56	0.000***
PC2	3.73	2.97±0.45	0.012*
PC3	0.82	0.83±0.26	1 ^{ns}
PC4	0.78	0.68±0.18	1 ^{ns}

ns: not significant

The results of the PCA biplot, illustrating the relationship between the physicochemical and functional parameters of the formulated flours, are presented in Figure 1. The use of multivariate analysis effectively discriminated between the different formulations, a method widely validated in the characterization of food quality.Flours FC1 and FC2 exhibit high energy potential, whereas FC3, FC4, and FC5 display high nutritional potential in terms of protein and fiber content. Formulations rich in protein and fiber are considered to possess high nutritional value, contributing to human health. Samples FC4 and FC5 cluster together, showing a strong correlation with protein and ash content. This association is likely attributable to the milling process used to reduce the grains into fine powder; this is typical of flours produced via dry fractionation processes, where protein fractions retain mineral salts located in the peripheral layers of the grain.

The projection of FC3 indicates that its functionality is not solely due to its protein content, but likely results from a synergy between its fiber content and protein structure. Hydrophilic interactions, mediated by hydrogen bonding between the hydroxyl groups of the polysaccharides and the amino acid side chains, are the primary determinants of Water Absorption Capacity (WAC). From an industrial perspective, the distinct positioning of FC3 suggests specific potential for applications in bakery or fine charcuterie, where water retention is critical for process yield and product texture.

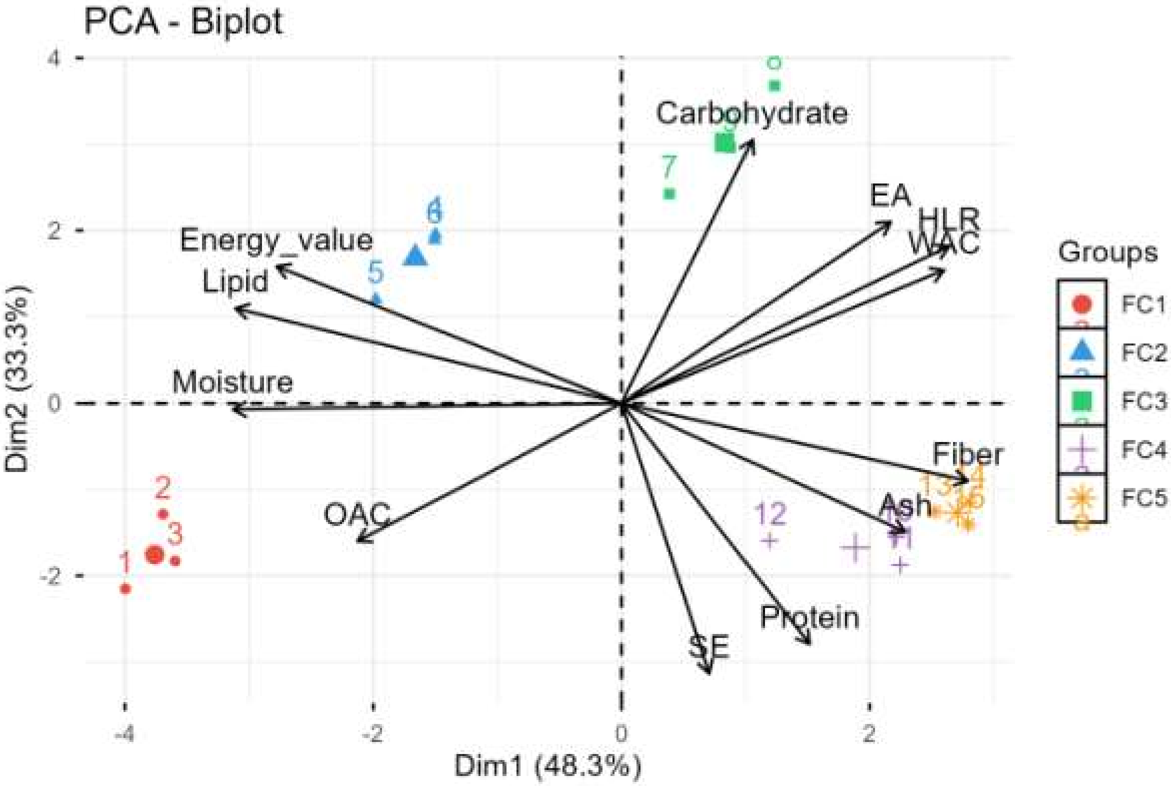

Figure1: Graphical representation of the PCA-Biplot analysis of physicochemical and functional parameters in formulated flours

Table IV : Euclidean distance matrix betweensamples

	FC1	FC2	FC3	FC4	FC5
FC1	0.00	25.01	30.92	23.76	25.55
FC2	25.01	0.00	15.86	21.36	17.76
FC3	30.92	15.86	0.00	25.01	20.05
FC4	23.76	21.36	25.01	0.00	11.68
FC5	25.55	17.76	20.05	11.68	0.00

The minimum Euclidean distance observed between formulations FC4 and FC5 (11.68) highlights a remarkable structural homogeneity, suggesting that beyond a certain threshold of tamarind pulp incorporation, physicochemical properties tend toward stabilization. This convergence indicates that the variations in tamarind concentration between these two formulations no longer significantly alter the composite flour matrix, which may serve as an indicator of saturation in the starch-binding capacity.In contrast, formulation FC1 stands out markedly due to its significant distance from the other specimens. This distinctiveness is primarily attributable to a nutrient content closer to that of the control, reflecting a limited influence of tamarind enrichment on its initial functional properties. While FC4 and FC5 exhibit a stabilized structure, FC1 is characterized by more volatile water absorption capacity (WAC) and solubility properties, indicating a less cohesive matrix. This difference underscores the critical role of tamarind pulp powder concentration: whereas FC1 retains the intrinsic characteristics of the sprouted maize and soybean flours, the more enriched formulations (FC4 and FC5) benefit from structural modifications induced by the fiber and pectic compounds of the tamarind, thereby altering their rheological behavior.

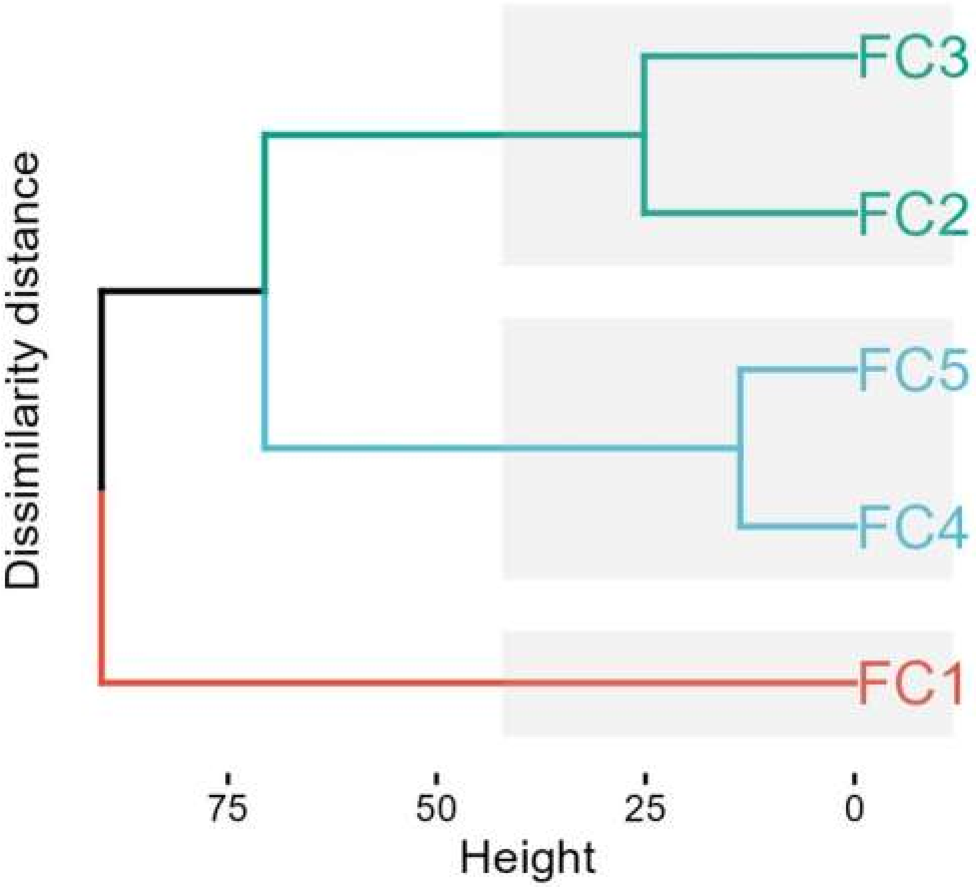

Figure 2 :HCA dendrogram of samples FC1 to FC5. Ward's method. D2, Euclidean distance. Cophenetic coefficient = 0.857

Hierarchical Cluster Analysis (HCA)

Hierarchical Cluster Analysis (HCA) based on the twelve physicochemical parameters grouped the five samples into three distinct clusters with a cophenetic correlation coefficient of 0.86, indicating a faithful representation of the Euclidean distance matrix. FC1 forms an isolated cluster due to its high distance values from the other samples, ranging from 23.77 to 30.92.Samples FC2 and FC3 constitute a second cluster with an inter-sample distance of 15.86. The third cluster groups FC4 and FC5, which exhibit the lowest inter-sample distance of 11.68. The separation of FC1 can be attributed to its specific moisture, fiber, and protein content.The proximity of FC4 and FC5 suggests a similar composition, corroborated by their low Euclidean distance. This three-group structure is consistent with the PCA, where Dim1 and Dim2 also separate FC1 from the other samples.A methodological limitation of this study is the high variables-to-samples ratio, as the number of physicochemical and functional variables exceeds the number of composite flour formulations. To mitigate the risk of overfitting associated with this p>>n context, we validated the PCA structure using a permutation test and confirmed the reliability of the clustering with the cophenetic correlation coefficient. Despite these internal validations, external validation on a larger, independent sample set remains necessary. Future work should include sensory acceptability tests, shelf-life studies, and the evaluation of formulation FC3 at both pilot and industrial scales to confirm its application and relevance to consumers.

Conclusion:-

This study demonstrates that tamarind pulp enrichment significantly modifies the physicochemical and functional profile of sprouted maize and soybean composite flours. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), validated by a permutation test, successfully discriminated the formulations and identified

FC3 as a technologically promising blend for water-dependent food systems. To facilitate industrial adoption, future research should validate these findings through sensory evaluation and pilot-scale trials.

Acknowledgements:-

I would like to express my deep gratitude and thanks to the Head of the Nutrition and Pharmacology Department at Félix Houphouët-Boigny University (Abidjan, Côte d'Ivoire) and the scientific director for supervising and directing this research.

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