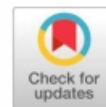


Original Research Article

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Deciphering the role of phenolics and antioxidants in rancidity development of pearl millet flour during storage



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ABSTRACT

Pearl millet flour undergoes rapid post-milling rancidity, yet the interplay between lipid deterioration and endogenous antioxidant depletion remains poorly characterized. This study assessed hydrolytic and oxidative rancidity, concurrent with phenolic and antioxidant dynamics, in genotypes Chadi Bajra and MPMH-17 during 60 days of ambient storage. Lipid content declined progressively in both genotypes, from 5.43% to 4.58% in Chadi Bajra and 6.67% to 5.21% in MPMH-17. Acid value increased sharply to 18.16 mg KOH/g and 24.73 mg KOH/g by 30 days, while peroxide value peaked at 43.39 and 70.24 meq/kg, confirming rapid hydrolysis and hydroperoxide formation. Total phenolics decreased substantially (Chadi Bajra: 19.70 to 8.67 mg/100 g; MPMH-17: 16.47 to 5.81 mg/100 g), accompanied by marked reductions in thiols and FRAP activity, indicating progressive antioxidant exhaustion. Correlation and PCA analysis showed that declining antioxidant capacity aligned strongly with rising rancidity markers, with MPMH-17 consistently clustering toward high-deterioration vectors. Collectively, the results demonstrate that rancidity progression is initiated early, driven by coordinated lipid hydrolysis and oxidation, and amplified by depletion of phenolic and thiol-based antioxidants. The pronounced susceptibility of MPMH-17 highlights genotype-dependent biochemical resilience and underscores the need to integrate antioxidant traits when evaluating flour shelflife.

Keywords: Rancidity, Pearl Millet, Antioxidants, Phenolics, Acid and Peroxide Value.

1. Introduction

Pearl millet is a climate-resilient cereal valued for its nutritional density and widespread use in traditional diets. Despite these advantages, its utilization in flour-based products is constrained by extremely short shelf-life, primarily due to the rapid development of rancidity after milling (1). Compared with other cereals, pearl millet flour deteriorates unusually fast, generating off-flavors and bitterness within days of storage (2). This instability limits consumer acceptance and restricts the potential of the crop for broader food applications.

Rancidity in pearl millet arises from a combination of hydrolytic and oxidative degradation of its lipidrich endosperm(3). Endogenous lipases rapidly hydrolyze triacylglycerols, releasing free fatty acids (FFAs) that subsequently undergo oxidation to form hydroperoxides, secondary volatiles, and

aroma-active compounds (4,5). Conventional indicators such as lipid content, peroxide value (PV), and acid value (AV) reliably track these reactions; however, these biochemical metrics alone do not explain why different genotypes exhibit markedly different shelf-life behavior despite similar storage conditions (6).

Pearl millet contains a diverse pool of phenolics, tannins, thiols, and other antioxidant constituents that are known to quench lipid-derived radicals and delay oxidative deterioration (7). These molecules are central to the cereal's biochemical defense system, influencing both storage stability and functional quality (8). While several studies have characterized phenolic profiles in fresh grains or during processing, their dynamic behavior during storage, especially their depletion, transformation, or polymerization, remains poorly understood.

Despite extensive work on lipid breakdown pathways, the direct relationship between rancidity progression and the temporal depletion of antioxidant constituents has not been deciphered in pearl millet flour (9). Specifically, it is unclear how changes in total phenolics, tannins, thiols, and total antioxidant capacity correspond to the rise in FFAs, peroxides, and other rancidity markers (7).

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DOI: <https://doi.org/10.21276/AATCCReview.2026.14.02.100>

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The mechanistic role of phenolic loss, whether as a cause or a consequence of lipid oxidation, remains unresolved. Moreover, very few studies have compared genotypes differing in rancidity susceptibility to determine whether antioxidant reserves underlie these differences.

The present study evaluated two contrasting pearl millet genotypes—Chadi Bajra and MPMH-17, to track simultaneous changes in lipid deterioration indicators and antioxidant-associated traits during 60 days of storage. By integrating univariate biochemical assays with correlation analysis and principal component analysis, this study aimed to decipher how antioxidant depletion and phenolic transformation influence rancidity progression, and whether these biochemical trajectories explain genotype-specific differences in storage stability (10).

2. Materials and Methods

2.1. Biological Material, Flour Processing, Ageing, and Sample Collection

Pearl millet grains of two contrasting genotypes—Chadi Bajra and MPMH-17, were cleaned to remove dust, stones, and extraneous material. Clean grains were milled using a laboratory cyclone mill to obtain fresh wholegrain flour under identical milling conditions, and flour from each genotype was transferred into airtight, opaque, food-grade containers and stored under dark, household-like ambient conditions to simulate typical domestic storage environments. Flour samples were collected at 0, 30, and 60 days after milling (DAM) to monitor temporal biochemical changes associated with rancidity progression. All collected samples were immediately sealed and stored at -20°C until biochemical analysis.

2.2. Lipid Extraction and Quantification

Lipids were extracted using a standard Soxhlet apparatus with food-grade *n*-hexane as the extraction solvent. 5 g of flour placed in a thimble and refluxed for 6 hours to ensure complete extraction of solvent-soluble lipids.

After extraction, the solvent was evaporated under reduced pressure, and the recovered lipid fraction was dried to constant weight (11). Lipid content was expressed gravimetrically as percentage of oil per gram of flour (w/w).

2.3. Determination of rancidity marker

Peroxide value (PV) and acid value (AV) of the flour were estimated following the protocol described by (12) with minor modifications.

2.3.1. Peroxide Value (PV)

The acid value (AV) estimates the amount of free fatty acids present in the flour, which is the estimates of milligram of KOH requirement to neutralize the free fatty acid. AV was measured using standard methods outlined by the Goswami et al., (2020) with minor adjustments. One gram of flour was added to the freshly neutralized ethyl alcohol (10 mL) and heated to the boiling temperature. 100 μL of phenolphthalein indicator was added before titrating it with a 0.1 N KOH solution. AV (mg KOH g^{-1} flour) was calculated as follows:

$$AV = (56.1 * N * A) / W$$

where A corresponds to the volume of KOH (mL), 56.1 is the molecular weight of 0.1 N KOH, W stands for the weight of sample, and N is the normality of the KOH solution.

2.3.2 Estimation of peroxide value (PV)

Peroxide values were estimated using the method outlined in (13). One gram flour sample was added to the 6 mL of an acetic acid-chloroform mixture (3:2 ratio), and 100 μL of freshly prepared saturated KI solution was added before incubating it for 10 min. subsequently, 6 mL of water and 200 μL of starch (1%) solution was added, which turns the solution blue-black. The solution was then titrated with 0.1 N sodium thiosulfate until the color disappeared. A control experiment without flour was used as a reference. PV was calculated in milliequivalents of peroxide per kilogram of flour using the following formula:

$$PV = (A - B) * \left(\frac{1000}{W}\right) * N$$

where PV is the peroxide value, A is the titration volume of $\text{Na}_2\text{S}_2\text{O}_3$ (mL) in the sample, B is the titration volume of $\text{Na}_2\text{S}_2\text{O}_3$ (mL) in the blank, N is the normality of the standard $\text{Na}_2\text{S}_2\text{O}_3$ solution, and W is the weight of the flour (g).

2.4. Estimation of Total Phenolic Content and Total Tannin Content

2.4.1 Total Phenolic Content (TPC)

Total phenolic content was determined following the Folin–Ciocalteu method as described by (14) with minor modifications. Briefly, 1 g of flour was extracted with 80% methanol under constant agitation and centrifuged at $10,000 \times g$. An aliquot of the supernatant was mixed with Folin–Ciocalteu reagent and incubated for 5 min, followed by the addition of 7% sodium carbonate. After incubation at room temperature for 30 minutes, absorbance was recorded at 765 nm. TPC was quantified using a gallic acid standard curve and expressed as mg gallic acid equivalents (GAE) per g flour.

2.4.2 Total Tannin Content (TTC)

Total tannins were measured following the vanillin–HCl method widely used for pearl millet and other millets (15). Flour (1 g) was extracted with 1% HCl in methanol, and the supernatant was reacted with freshly prepared vanillin–HCl reagent. The mixture was incubated at room temperature for 20 minutes, and absorbance was measured at 500 nm. TTC was quantified using a catechin calibration curve and expressed as mg catechin equivalents (CE) per g flour.

2.5. Estimation of Total Thiol Content and Total Antioxidant Capacity

2.5.1 Total Thiol Content

Total thiols were estimated using the Ellman's reagent (DTNB) method, following standard protocols applied to cereal flours, including pearl millet (16). Flour extracts were prepared by homogenizing 1 g of sample in Tris–EDTA buffer (pH 8.0) and centrifuging at $10,000 \times g$. An aliquot of the supernatant was mixed with 5,5'-dithiobis-(2-nitrobenzoic acid) (DTNB), and the formation of the yellow-colored TNB product was measured at 412 nm. Total thiol content was calculated using the molar extinction coefficient (ϵ) = $13,600 \text{ M}^{-1} \text{ cm}^{-1}$ and expressed as μmol thiols per g flour.

2.5.2 Total Antioxidant Capacity (FRAP Assay)

Total antioxidant activity was quantified using the Ferric Reducing Antioxidant Power (FRAP) assay, following (17) with modifications reported for pearl (18). Methanolic flour extracts were prepared by shaking 1 g of flour with 80% methanol and centrifugation.

The supernatant (100 μ L) was mixed with FRAP reagent (300 mM acetate buffer, 10 mM TPTZ, and 20 mM $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) pre-warmed to 37 °C. After incubation for 30 minutes, absorbance was recorded at 593 nm. Antioxidant capacity was expressed as $\mu\text{mol Fe}^{2+}$ equivalents per g flour using a ferrous sulfate calibration curve.

2.6. Statistical Analysis

All measurements were performed in triplicate ($n = 3$) for each genotype and storage stage. Data were analyzed using one-way ANOVA, and significant differences among means were identified using Tukey's HSD test ($p < 0.05$) with distinct letter groupings assigned accordingly. Pearson's correlation analysis and principal component analysis (PCA) were conducted to examine relationships among biochemical traits and to visualize sample clustering across ageing stages. Statistical analyses and plots were generated using Python (v3.13).

3. Results and Discussion

Pearl millet flour develops rancidity rapidly due to its high lipid content and strong lipase-lipoxygenase activities (19). However, the role of endogenous phenolics and antioxidants in moderating this deterioration remains unclear. To clarify these interactions, we quantified lipid degradation (acid value, peroxide value, lipid content) alongside total phenolics, tannins, thiols, and antioxidant capacity (FRAP) in two genotypes—Chadi Bajra and MPMH-17 at 30 and 60 DAM. This integrated biochemical profiling enables assessment of how antioxidant depletion contributes to rancidity progression and reveals genotype-specific differences consistent with earlier reports on variability in rancidity-related traits (20,21).

3.1 Lipid Dynamics During Storage

Lipid content decreased consistently in both genotypes during storage, from 5.43% to 4.58% in Chadi Bajra and 6.67% to 5.21% in MPMH-17, indicating sustained hydrolytic cleavage of triacylglycerols (Fig. 1.). This decline reflects endogenous lipase activity that rapidly liberates free fatty acids following milling, a process well documented in pearl millet flour (4,22). MPMH-17 showed a greater reduction than Chadi Bajra, consistent with genotype-linked differences in lipid composition and lipolytic potential reported in earlier studies (20,21). These patterns confirm that hydrolysis is initiated early during storage and progresses in a genotypedependent manner, influencing subsequent oxidative deterioration.

3.2 Peroxide and Acid Values Indicate Accelerated Oxidation and Hydrolysis

Peroxide value increased sharply from 0 to 30 DAM in both genotypes, reaching 43.39 meq/kg in Chadi Bajra and 70.24 meq/kg in MPMH-17, indicating rapid accumulation of lipid hydroperoxides soon after milling (Fig. 2A). The slight decline at 60 DAM reflects decomposition of primary peroxides into secondary oxidation products, a typical progression of oxidative rancidity (23,24). Acid value exhibited a sustained rise, from 5.70 to 18.16 and declined to 12.91 mg KOH/g in Chadi Bajra (Fig. 2B), confirming continuous lipase-mediated hydrolysis (25). Consistently higher PV and AV in MPMH-17 indicate greater susceptibility, aligning with genotype-linked differences in lipid composition and enzyme activity reported in pearl millet (26,27).

3.3 Total Phenolics and Tannins Decline with Storage Progression

Total phenolic content (TPC) declined steadily during storage in both genotypes, decreasing from 19.70 to 8.67 mg/100 g in Chadi Bajra and 16.47 to 5.81 mg/100 g in MPMH-17 (Fig. 3A). This reduction reflects progressive oxidation and polymerization of phenolic compounds, a pattern widely reported in cereal flour during ageing (18,28). Total Tannin content levels showed genotype-dependent behavior, remaining relatively stable in early storage but increasing slightly by 60 DAM in Chadi Bajra, suggesting oxidative cross-linking and pigment formation during advanced rancidity stages (Fig.3B). MPMH-17 exhibited a modest rise from 8.57 to 13.00 mg/100 g, consistent with phenolic-protein and phenolic-lipid interactions documented in stored millet flours (2,29). The sharper decline in TPC in MPMH-17 indicates weaker antioxidant buffering and supports its higher susceptibility to rancidity.

3.4 Thiol Depletion and Declining Antioxidant Capacity Reflect Progressive Oxidative Stress

Thiol content decreased markedly during storage, falling from 8.70 to 3.93 mM/g in Chadi Bajra and 3.67 to 1.47 mM/g in MPMH-17 (Fig. 4A). This decline indicates progressive oxidation of sulfhydryl groups, which serve as key redox buffers in cereal flour (16). The sharper reduction in MPMH-17 suggests accelerated depletion of reactive thiol under higher oxidative load. FRAP activity exhibited a parallel decrease, from 10.70 to 2.94 mmol FeSO_4/g in Chadi Bajra and 6.10 to 1.53 mmol FeSO_4/g in MPMH-17, demonstrating a substantial reduction in total antioxidant capacity (Fig. 4B). These patterns agree with reports that endogenous antioxidants diminish rapidly during storage, weakening the resistance of millet flours to lipid oxidation (7,12). The combined decline in thiol and FRAP underscores reduced antioxidant buffering, supporting the higher rancidity observed in MPMH-17.

3.5 Correlation and PCA Analysis Reveal Coordinated Lipid and Antioxidant Depletion

Correlation analysis showed strong positive associations between acid value, peroxide value, and storage duration, confirming coordinated hydrolytic and oxidative deterioration (Fig. 5A). Lipid content exhibited a strong negative correlation with both AV and PV, reflecting depletion of triacylglycerols as free fatty acids and hydroperoxides accumulated. Antioxidant traits—TPC, thiols, and FRAP—were negatively correlated with rancidity markers, indicating that progressive antioxidant loss accompanies lipid oxidation, a trend consistent with earlier biochemical assessments of millet flours (22,30).

PCA further resolved these relationships: samples at 30 and 60 DAM clustered separately from 0 DAM, driven by elevated AV and PV and reduced phenolics and antioxidant capacity (Fig. 5B-C). The separation between genotypes, with MPMH-17 positioned closer to high-rancidity vectors, supports its greater susceptibility, aligning with genotype-specific variation reported previously (18,25). Together, the multivariate patterns reaffirm that antioxidant depletion is tightly coupled with rancidity progression.

Overall, the integrated assessment of lipid indices and antioxidant traits demonstrates that rancidity progression in pearl millet flour is driven by tightly linked hydrolytic and oxidative reactions, accelerated by depletion of phenolics, thiols, and total antioxidant capacity.

The sharper deterioration in MPMH-17 highlights clear genotype-dependent susceptibility. These biochemical trajectories indicate that antioxidant exhaustion is a central trigger for rapid rancidity, underscoring the need to consider both lipid composition and antioxidant reserves when evaluating flour stability.

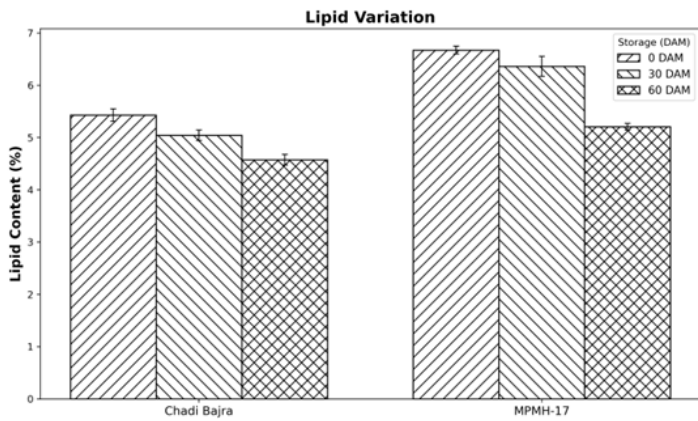


Fig.1: Lipid content (%) of pearl millet flour as influenced by genotype (Chadi Bajra and MPMH-17) and storage duration (0, 30, and 60 days after milling, DAM). Bars represent mean \pm SEM (n = 3).

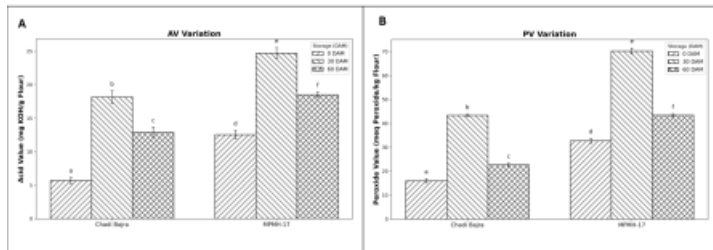


Fig.2: Peroxide value (A) and acid value (B) variation in pearl millet flour across two genotypes (Chadi Bajra and MPMH-17) during storage at 0, 30, and 60 days after milling (DAM). Bars represent mean \pm SEM (n = 3), and distinct hatch patterns denote storage duration. Different letters above bars indicate significant differences among genotype \times storage combinations according to Tukey's HSD ($p < 0.05$).

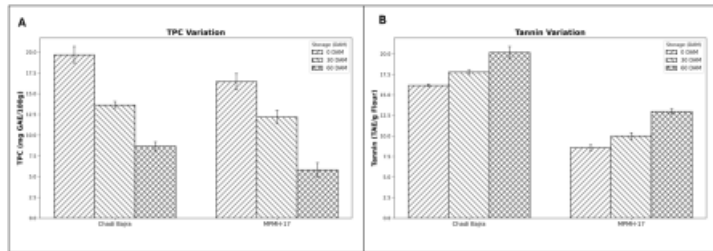


Fig.3: (A) Total phenolic content (TPC) and (B) Total Tannin Content variation in pearl millet flour across two genotypes (Chadi Bajra and MPMH-17) during storage at 0, 30, and 60 days after milling (DAM). Bars represent mean \pm SEM (n = 3). Hatch patterns denote storage duration. (A) TPC expressed as mg GAE / 100 g flour. (B) Tannin content expressed as TAE / g flour. Different lowercase letters indicate statistically significant differences among genotype \times storage combinations [Tukey HSD, $p < 0.05$].

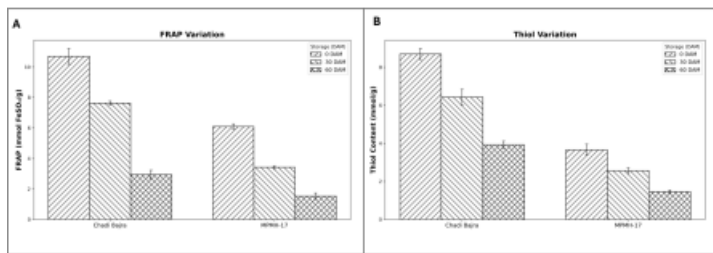


Fig.4: (A) Antioxidant activity (FRAP) and (B) Thiol content variation in pearl millet flour across two genotypes (Chadi Bajra and MPMH-17) during storage at 0, 30, and 60 days after milling (DAM). Bars represent mean \pm SEM (n = 3), with hatch patterns indicating storage duration. (A) Ferric reducing antioxidant power (FRAP) expressed as mmol FeSO₄/g flour. (B) Thiol content expressed as mmol/g flour. Different lowercase letters indicate statistically significant differences among genotype \times storage combinations [Tukey HSD, $p < 0.05$].

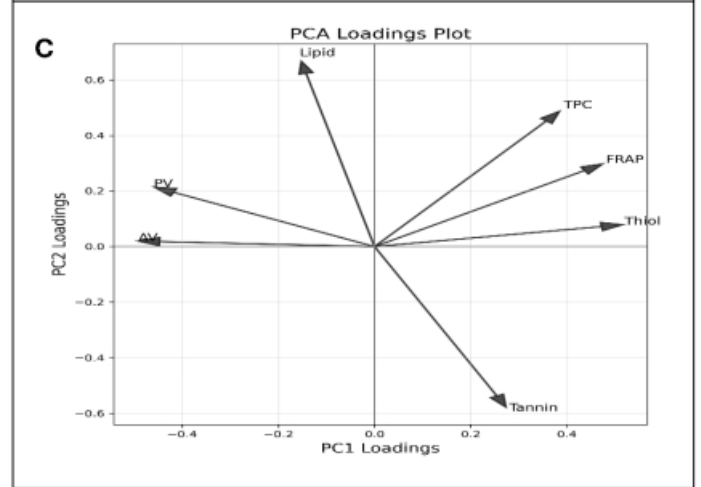
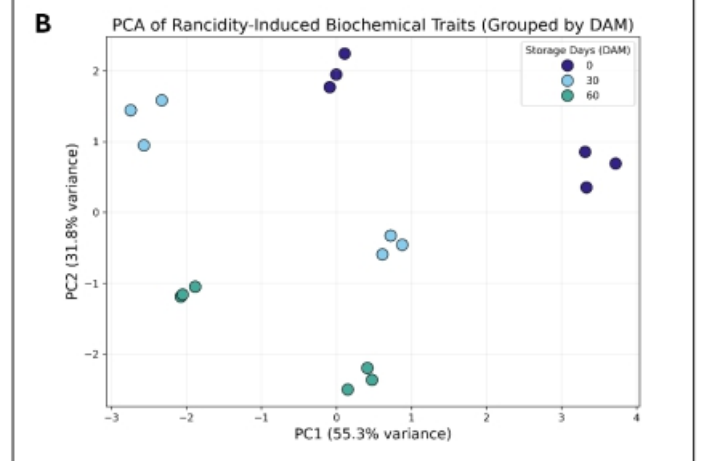
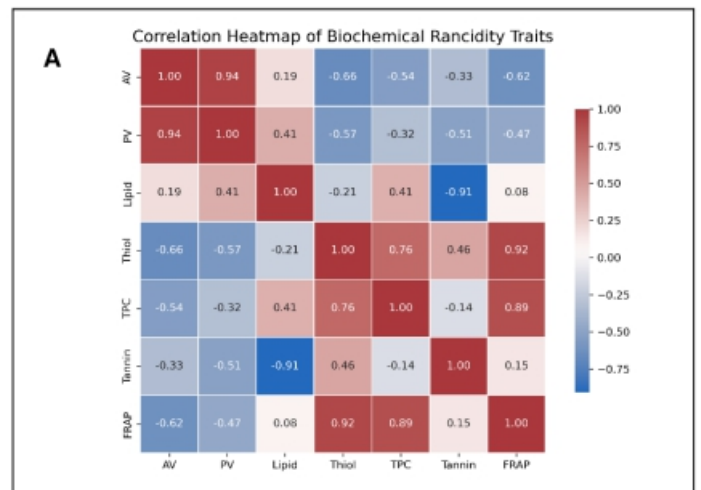


Fig.5: Multivariate overview of biochemical rancidity markers in pearl millet flour during storage. (A) PCA loadings showing trait contributions to PC1–PC2 separation. (B) PCA scores, grouped by storage duration (0, 30, 60 DAM), illustrating clear temporal shifts associated with rancidity progression. (C) Correlation heatmap summarizing relationships among oxidative and antioxidant traits, with AV–PV strongly aligned and antioxidant traits inversely associated with rancidity markers.

4. Conclusion

This study demonstrates that rancidity in pearl millet flour is governed by closely coupled hydrolytic and oxidative reactions initiated soon after milling. Declines in lipid content, coupled with sharp increases in acid and peroxide values, confirm rapid enzymatic and oxidative deterioration. Parallel depletion of phenolics, thiols, and antioxidant capacity shows that loss of endogenous antioxidant buffering is a key driver of rancidity progression. The consistently stronger deterioration in MPMH-17 underscores clear genotype-dependent susceptibility.

These findings highlight the need to integrate lipid composition, enzyme activity, and antioxidant reserves when assessing storage stability or developing strategies to extend flour shelf life.

Acknowledgements

The authors gratefully acknowledge financial support from the ICAR–Indian Institute of Millets Research, Hyderabad, under the GCoE Project (Grant No. GCoE TG3361/12-258), which enabled the successful execution of this study. We also thank the Graduate School, ICAR–IARI, New Delhi, for providing academic support and Ph.D. assistance. The authors further acknowledge all institutional facilities and technical support that contributed to the completion of this work.

Funding Sources

This research was financially supported by the ICAR–Indian Institute of Millets Research, Hyderabad, through the GCoE Project (Grant No. GCoE TG3361/12-258). The funding agency had no role in the study design; data collection, analysis, or interpretation; manuscript writing; or the decision to submit this article for publication.

Conflict of Interest

Authors declare no conflict of interest

References

- Rani S, Singh R, Sehrawat R, Kaur BP, Upadhyay A. Pearl millet processing: a review. *Nutr Amp Food Sci*. 2018 Feb 12;48(1):30–44.
- Ramya C S, Manik SF, Malathi G, Kamalasundari S, Singh B, Angmo D, et al. Pearl Millet: A Critical Review on Processing Techniques and Its Products. *J Sci Res Rep*. 2024 Mar 9;30(4):274–86.
- Chitranashi A, Kumari S, ... Exploring the nutritional composition of pearl millet: insights into rancidity development and strategies for prevention. *Vet Farm Front E ...* [Internet]. 2024;(Query date: 2025-12-20 17:11:23). Available from: <https://vetfarmfrontier.com/wp-content/uploads/2024/04/7.-Chitranashi-et-al.-March-2024-Vol.-1-Issue-1-28-34.pdf>
- Aher RR, Reddy PS, Bhunia RK, Flyckt KS, Shankhapal AR, Ojha R, et al. Loss-of-function of triacylglycerol lipases are associated with low flour rancidity in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Front Plant Sci* [Internet]. 2022 Oct 4 [cited 2024 Nov 18];13. Available from: <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.962667/full>
- Kumar RR, Bhargava DV, Pandit K, Goswami S, Mukesh Shankar S, Singh SP, et al. Lipase – The fascinating dynamics of enzyme in seed storage and germination – A real challenge to pearl millet. *Food Chem*. 2021 Nov;361:130031.
- Aher RR, Bhunia RK, Kaur S, Sanivarapu H, Palakolanu SR, Taleon V, et al. Exploring rancidity in pearl millet flour: A lipidomic and biochemical approach. *J Cereal Sci*. 2025 Nov 1;126:104320.
- Ali A, Kumar RR, Vinutha T, Singh T, Singh SP, Satyavathi CT, et al. Grain phenolics: critical role in quality, storage stability and effects of processing in major grain crops—a concise review. *Eur Food Res Technol*. 2022 Aug;248(8):2197–213.
- Chen MH, Bergman CJ, McClung AM. Hydrolytic rancidity and its association with phenolics in rice bran. *Food Chem*. 2019 July 1;285:485–91.
- Bhargavi HA, Singh SP, Goswami S, Yadav S, Aavula N, Shashikumara P, et al. Deciphering the genetic variability for biochemical parameters influencing rancidity of pearl millet (*Pennisetum glaucum* L. R. Br.) flour in a set of highly diverse lines and their categorization using rancidity matrix. *J Food Compos Anal*. 2024 Apr 1;128:106035.
- Goswami S, Asrani P, Ansheef Ali TP, Kumar RD, Vinutha T, Veda K, et al. Rancidity Matrix: Development of Biochemical Indicators for Analysing the Keeping Quality of Pearl Millet Flour. *Food Anal Methods*. 2020 Nov 1;13(11):2147–64.
- Aher R, Reddy P, Bhunia R, Flyckt K, ... Loss-of-function of triacylglycerol lipases are associated with low flour rancidity in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Front Plant ...* [Internet]. 2022;(Query date: 2025-12-20 17:11:23). Available from: <https://www.frontiersin.org/articles/10.3389/fpls.2022.962667/full>
- Goswami S, Asrani P, Ansheef Ali TP, Kumar RD, Vinutha T, Veda K, et al. Rancidity Matrix: Development of Biochemical Indicators for Analysing the Keeping Quality of Pearl Millet Flour. *Food Anal Methods*. 2020 Nov 1;13(11):2147–64.
- Vanhnen L, Savage G. The use of peroxide value as a measure of quality for walnut flour stored at five different temperatures using three different types of packaging. *Food Chem* [Internet]. 2006;(Query date: 2025-12-20 17:51:41). Available from: <https://www.sciencedirect.com/science/article/pii/S0308814605005972>
- Pushparaj FS, Urooj A, Pushparaj FS, Urooj A. Antioxidant Activity in Two Pearl Millet (*Pennisetum typhoideum*) Cultivars as Influenced by Processing. *Antioxidants*. 2014 Feb 12;3(1):55–66.
- Price ML, Butler LG. ACS Publications. American Chemical Society; 2002 [cited 2025 Dec 7]. Rapid visual estimation and spectrophotometric determination of tannin content of sorghum grain. Available from: <https://pubs.acs.org/doi/pdf/10.1021/jf60214a034>
- Kumar RR, Babu H P, Hasija S, Gampa M, Goswami S, T. V, et al. Thiol-based redox sensing regulates the yellow pigment and antioxidant accumulation and improves the nutritional quality of wheat grains (*Triticum aestivum* L.). *Front Plant Sci* [Internet]. 2025 May 30 [cited 2025 Dec 7];16. Available from: <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2025.1488697/full>
- Benzie IF, Strain JJ. The ferric reducing ability of plasma (FRAP) as a measure of “antioxidant power”: the FRAP assay. *Anal Biochem*. 1996 July 15;239(1):70–6.
- Ali A, Kumar RR, T. V, Bansal N, Bollinedi H, Singh SP, et al. Characterization of biochemical indicators and metabolites linked with rancidity and browning of pearl millet flour during storage. *J Plant Biochem Biotechnol*. 2023 Mar 1;32(1):121–31.
- Kumar RR, Bhargava DV, Pandit K, Goswami S, Mukesh Shankar S, Singh SP, et al. Lipase – The fascinating dynamics of enzyme in seed storage and germination – A real challenge to pearl millet. *Food Chem*. 2021 Nov 1;361:130031.
- Pallavi M, Reddy PS, Ratnavathi CV, Krishna KVR. Genetic Variability and Diversity for Rancidity and Associated Characters in Pearl Millet (*Pennisetum Glaucum* L.) [Internet]. In Review; 2023 [cited 2024 Dec 19]. Available from: <https://www.researchsquare.com/article/rs-2427655/v1>
- Pallavi M, Reddy PS, Ratnavathi CV, Krishna KVR. Genetic Variability and Diversity for Rancidity and Associated Characters in Pearl Millet (*Pennisetum glaucum* L.). *J Exp Agric Int*. 2024 July 4;46(7):928–39.

22. Kumar RR, Kumar A, Vinutha T, Goswami S, Kumar S, Singh S, et al. Characterising the enzyme-driven metabolic shifts in rancid pearl millet flour using metabolomics approaches: a step towards improving quality and shelf-life. *Front Nutr* [Internet]. 2025 Oct 23 [cited 2025 Nov 29];12. Available from: <https://www.frontiersin.org/journals/nutrition/articles/10.3389/fnut.2025.1691522/full>
23. Ansheef Ali. Characterization of biochemical indicators and metabolites linked with rancidity and browning of pearl millet flour during storage. *J Plant Biochem Biotechnol*. 2023;
24. Machado M, Rodriguez-Alcalá LM, Gomes AM, Pintado M. Vegetable oils oxidation: mechanisms, consequences and protective strategies. *Food Rev Int*. 2023 Aug 25;39(7):4180–97.
25. Yarrakula S, Mummaleti G, Toleti KS, Saravanan S. Functional characteristics and storage stability of hot air assisted radio frequency treated pearl millet. *Food Prod Process Nutr*. 2024 July 6;6(1):60.
26. Chitranshi, Abhishek., Vinutha. T, Kumar, Mahesh., Prakash, Jyoti. Combating rancidity in pearl millet flour: Assessing the efficacy of physical treatments on lipoxygenase activity. *Int J Adv Biochem Res*. 2024;8(6):648–54.
27. Tiwari A, Jha S k., Pal R k., Sethi S, Krishan L. Effect of Pre-Milling Treatments on Storage Stability of Pearl Millet Flour. *J Food Process Preserv*. 2014;38(3):1215–23.
28. Meena KK, Meena S, Joshi M, Dhotre AV. Nutritional and functional exploration of pearl millet and its processing and utilization: An overview. *Food Humanity*. 2024 Dec 1;3:100334.
29. Deka G, Dutta H, Sharma P. A review: Hydrothermal processing of millets and effect on techno-functional and nutritional properties. *J Food Process Eng*. 2023 Sept;46(9):e14408.
30. Yogendra K, Sanivarapu H, Avuthu T, Gupta SK, Durgalla P, Banerjee R, et al. Comparative Metabolomics to Unravel the Biochemical Mechanism Associated with Rancidity in Pearl Millet (*Pennisetum glaucum* L.). *Int J Mol Sci*. 2024 Jan;25(21):11583.