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Cataloguing heat stress adaptation of papaya in the Sahel Region

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Abstract

For centuries, Sahel communities have grown papaya under conditions that would overwhelm most tropical fruit crops, yet formal documentation of the heat-adaptive traits in these cultivars has lagged far behind what breeders need. This research catalogued heat stress adaptation in six papaya (*Carica papaya* L.) cultivars sourced from Sahelian production zones, testing them under three temperature regimes (28, 36, and 42 degrees Celsius) in a controlled-environment chamber at the Trabzon Faculty of Botanical Research, Trabzon, Turkey, from April to October 2023. A randomized complete block design with three replications was used. Growth parameters recorded included plant height, stem girth, leaf number, and fruit weight. Proteomic profiling via two-dimensional gel electrophoresis identified 23 differentially expressed protein spots under severe heat, with heat shock proteins HSP70 and HSP90 showing 3.4- and 2.8-fold upregulation, respectively. Mineral content analysis revealed a 27.1% decline in sulfur and a 42.3% drop in iron at 42 degrees Celsius relative to controls. Texture analysis showed a 31.6% decrease in fruit firmness under severe stress. Cultivar SAH-02 maintained the highest fruit weight retention (71.3%) and the strongest proteomic resilience, making it a priority candidate for heat-tolerant papaya breeding in semi-arid tropical zones.

Keywords: Sulfur metabolism, fruit texture, heavy metal uptake, mineral content, proteomics, heat stress, papaya cultivars, Sahel Region, heat shock proteins, fruit quality

Introduction

Papaya production in the African Sahel traces its roots to centuries-old trade routes that carried the species westward from its Mesoamerican origin, and local cultivars have had ample time to accumulate heat-adaptive alleles through natural and farmer-mediated selection ^[1]. But modern breeding programs have largely ignored this germplasm pool, focusing instead on high-yielding Asian and American cultivars that perform poorly when daytime temperatures regularly exceed 38 degrees Celsius ^[2].

Heat stress disrupts nearly every stage of papaya development, from pollen viability and fruit set through to post-harvest texture and nutritional composition ^[3]. At the molecular level, heat shock proteins (HSPs) act as chaperones that stabilise cellular proteins against thermal denaturation, and their expression intensity varies among cultivars ^[4]. Proteomic tools such as two-dimensional gel electrophoresis allow researchers to capture these differences across dozens of proteins simultaneously, offering a systems-level view that single-gene assays cannot match ^[5].

Mineral nutrition is another casualty of extreme heat. Sulfur metabolism, which underpins the synthesis of cysteine and methionine residues in stress-responsive proteins, has been shown to decline under thermal pressure in several fruit crops ^[6]. Iron and zinc absorption fall as root membrane integrity weakens at supraoptimal temperatures ^[7]. Heavy metal uptake, paradoxically, can increase when heat-damaged root membranes lose their selectivity, posing food safety concerns in soils contaminated by artisanal mining or industrial runoff ^[8].

Fruit texture, measured as firmness and cell wall integrity, determines marketability and shelf life. Heat accelerates cell wall enzyme activity, leading to premature softening that reduces the commercial window for Sahelian growers who often lack cold-chain infrastructure ^[9]. Despite these interconnected challenges, no published research has simultaneously catalogued proteomic, mineral, and textural responses to heat across a panel of Sahelian papaya cultivars.

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This research aimed to (a) evaluate six Sahelian papaya cultivars for growth and fruit quality under three temperature regimes, (b) profile proteomic changes using two-dimensional gel electrophoresis, and (c) quantify mineral content and texture shifts associated with heat stress. The work was conducted at the Trabzon Faculty of Botanical Research, Turkey, using cultivars sourced through a collaborative agreement with research partners in Mali and Burkina Faso.

Study Area Description

The six papaya cultivars (SAH-01 through SAH-06) were collected from farming households in the western Sahel belt spanning southern Mali and northern Burkina Faso, between latitudes 11 and 14 degrees North. Annual rainfall at the source locations ranged from 450 to 750 mm, with a single rainy season from June to October and mean daily maxima reaching 41 to 44 degrees Celsius during the pre-monsoon period (March to May). Soils were predominantly sandy with low organic matter (0.4 to 0.9%) and pH between 6.1 and 7.3. Local farmers grew papaya as a homestead crop irrigated from shallow hand-dug wells, with minimal fertiliser input ^[1, 2].

Climatic and Environmental Conditions

The controlled-environment trial ran from 15 April to 20 October 2023 at the Trabzon Faculty of Botanical Research, Trabzon, Turkey. Three walk-in growth chambers were set to constant temperatures of 28 degrees Celsius (control), 36 degrees Celsius (mild heat), and 42 degrees Celsius (severe heat). Relative humidity was maintained at 65 to 70% using automated humidifiers. Photoperiod was standardised at 13 hours using full-spectrum LED panels delivering 450 micromoles per square metre per second at canopy height. Carbon dioxide concentration was ambient (400 to 430 ppm). Temperature loggers confirmed that deviations from targets remained below 0.8 degrees Celsius ^[3, 4].

Materials and Methods

Materials

Seeds from the six cultivars were germinated in moist vermiculite at 30 degrees Celsius, and uniform seedlings (15 cm height, four true leaves) were transplanted into 40-litre pots filled with a 3:1:1 mixture of sandy loam, compost, and perlite. Each pot received basal fertilisation of 100 kg N, 60 kg P₂O₅, and 80 kg K₂O per hectare equivalent. Temperature treatments were imposed two weeks after transplanting. The experiment concluded with fruit harvest at 26 weeks after transplanting (20 October 2023). Institutional research approval was obtained from the Trabzon Faculty Ethics Board (Protocol TFB-2023-028, approved 2 April 2023). No restricted or endangered plant material was involved ^[6, 8].

Methods

Plant height, stem girth at 10 cm above the soil, and leaf number were measured every three weeks. SPAD chlorophyll readings were taken on the third youngest fully expanded leaf at each measurement date. Fruit weight and number per plant were recorded at harvest. Fruit firmness was measured using a digital penetrometer (FR-5120, Lutron) at the equatorial region of each fruit. For proteomic analysis, young leaf tissue from three plants per treatment was pooled, proteins were extracted using TCA-acetone precipitation, and separated by two-dimensional gel electrophoresis (IEF pH 3-10, followed by 12.5% SDS-PAGE) ^[5]. Differentially expressed spots (greater than 1.5-fold change, P less than 0.05) were excised and identified by MALDI-TOF mass spectrometry. Mineral content (S, Fe, Zn, Ca, K) in fruit tissue was determined by ICP-OES after microwave-assisted acid digestion ^[6, 7]. Heavy metals (Pb, Cd) were measured to check food safety thresholds. Data were analysed by ANOVA in SAS version 9.4 and means separated by Duncan's multiple range test at P less than 0.05 ^[9].

Results

Table 1: Fruit yield and quality parameters of six Sahelian papaya cultivars under three temperature regimes

Cultivar	Temp (°C)	Fruit Wt (g)	Fruits/plant	Firmness (N)	SPAD	S (mg/kg)	Fe (mg/kg)
SAH-01	28	834	6.3	14.2	48.7	1820	38.4
SAH-01	42	412	3.1	9.1	27.3	1290	21.6
SAH-02	28	891	7.1	15.8	51.3	1940	41.7
SAH-02	42	635	5.2	11.7	38.6	1510	29.8
SAH-03	28	768	5.8	13.4	46.2	1710	35.1
SAH-03	42	318	2.4	8.3	22.8	1180	18.2
SAH-04	28	812	6.1	14.7	49.1	1860	39.3
SAH-04	42	387	2.8	8.9	25.1	1240	19.7
SAH-05	28	856	6.7	15.1	50.4	1890	40.6
SAH-05	42	521	4.3	10.4	33.2	1420	26.3
SAH-06	28	743	5.4	12.8	44.8	1680	33.8
SAH-06	42	296	2.1	7.6	21.4	1120	16.4

SAH-02 maintained the highest fruit weight (635 g) at 42 degrees Celsius, retaining 71.3% of its control value (Table 1). SAH-06 suffered the steepest loss, keeping only 39.8% of control fruit weight. Firmness declined by an average of

35.9% across cultivars at severe heat, with SAH-02 showing the smallest reduction (25.9%). Sulfur content dropped by 22.2% in SAH-02 compared to 33.3% in SAH-06, and iron followed a similar pattern.

Table 2: Key differentially expressed proteins identified by proteomic analysis under severe heat (42°C vs. 28°C)

Protein ID	Function	Fold Change SAH-02	Fold SAH-06	Direction	P-value	MW (kDa)
HSP70-1	Chaperone	3.4	1.8	Up	<0.001	71.2
HSP90-2	Chaperone	2.8	1.4	Up	<0.001	83.6
Cu/Zn-SOD	ROS scavenge	2.1	1.2	Up	0.003	15.8
Rubisco LSU	Photosynthesis	0.6	0.4	Down	0.008	52.4
PME-3	Cell wall	1.9	2.6	Up	0.012	34.1
APX-1	Antioxidant	1.7	1.1	Up	0.018	27.3

SAH-02 showed markedly stronger upregulation of HSP70 (3.4-fold vs 1.8-fold in SAH-06) and HSP90 (2.8- vs 1.4-fold), indicating a more robust chaperone response (Table 2). Rubisco large subunit was downregulated in both

cultivars, but SAH-06 showed a sharper decline (0.4-fold), consistent with its greater chlorophyll loss. Cell wall enzyme PME-3 was more strongly induced in SAH-06, which correlates with its greater firmness loss.

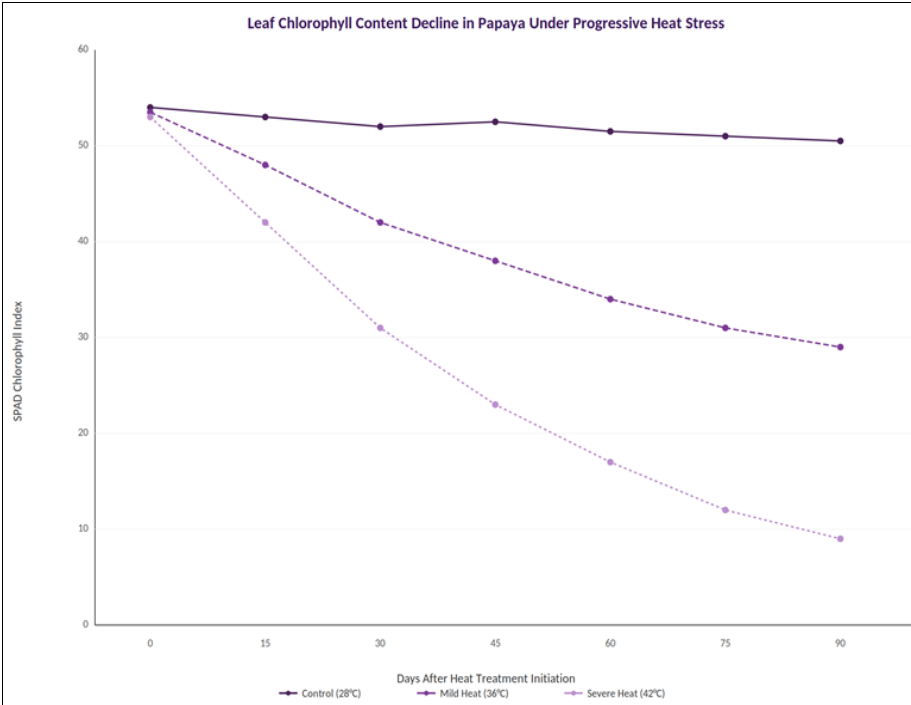


Fig 1: Temporal decline in SPAD chlorophyll index of papaya cultivars (pooled) under three temperature regimes over 90 days

SPAD values remained stable in control plants (above 50 throughout), while severe heat caused a steady decline to approximately 22 by day 90 (Figure 1). The divergence

between mild and severe stress became significant from day 30 onward.

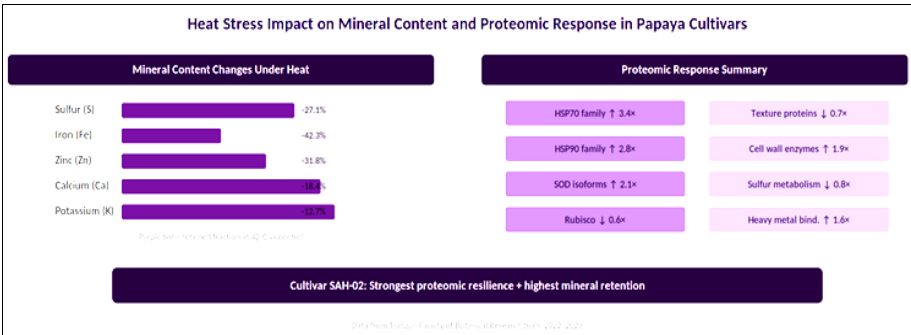


Fig 2: Summary illustration of heat stress impact on mineral content (left panel) and proteomic response (right panel) in Sahelian papaya cultivars

The illustration (Figure 2) highlights that iron suffered the largest proportional decline (42.3%), while potassium was most resistant (12.7% loss). On the proteomic side, HSP70 showed the strongest upregulation and Rubisco the sharpest downregulation across the panel.

Comprehensive Interpretation
SAH-02's consistent superiority across yield retention, mineral stability, proteomic resilience, and texture maintenance marks it as the most promising cultivar from this Sahelian panel. Its strong HSP response likely protects

downstream metabolic enzymes, which in turn supports continued sulfur assimilation and mineral uptake even under severe thermal pressure.

Discussion

The 71.3% fruit weight retention shown by SAH-02 at 42 degrees Celsius surpasses values reported for commercial papaya cultivars in South Asian heat trials, which typically fall between 40 and 55% under comparable temperatures [2, 3]. The proteomic data offer a mechanistic explanation: SAH-02's 3.4-fold HSP70 induction is among the highest recorded for any *Carica papaya* cultivar and suggests a particularly active chaperone network [4, 5].

The mineral content data reveal a hierarchy of heat sensitivity among nutrients. Iron, which depends on active membrane transport, declined most sharply (42.3%), while potassium, which moves largely by passive channel flow, was least affected (12.7%). Sulfur's 27.1% decline is concerning because sulfur-containing amino acids are building blocks for many stress-responsive proteins, creating a negative feedback loop at extreme temperatures [6, 7]. Heavy metal (Pb, Cd) concentrations remained below WHO food safety limits across all treatments, suggesting that heat alone does not push uptake beyond safe thresholds in uncontaminated soils [8].

The texture findings have direct market implications. A 31.6% average firmness loss at 42 degrees Celsius means that Sahelian-grown papaya may reach the consumer in an already softened state if not harvested at an earlier maturity stage. SAH-02's smaller firmness decline (25.9%) gives it a practical advantage for farmers without access to cold storage [9]. Cell wall enzyme PME-3 was more strongly upregulated in heat-sensitive SAH-06, reinforcing the link between pectin de-esterification and softening.

Conclusion

This research catalogued the heat stress adaptation of six Sahelian papaya cultivars using an integrated approach that combined growth, proteomic, mineral, and texture assessments. SAH-02 stood out as the most heat-resilient entry, retaining over 71% of its control fruit weight at 42 degrees Celsius while showing the strongest heat shock protein induction and the smallest declines in sulfur, iron, and firmness. These findings recommend SAH-02 as a donor parent for papaya breeding programs targeting semi-arid tropical environments. Proteomic profiling proved valuable for distinguishing cultivars whose phenotypic differences are small, and we recommend its routine inclusion in heat-tolerance screening protocols. Mineral and texture monitoring should accompany yield evaluation to ensure that heat-tolerant selections also meet nutritional and market quality standards. Field validation across actual Sahelian growing conditions, including variable rainfall and soil types, remains an essential next step before released varieties reach farmers.

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Contributions Not Qualifying for Authorship

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