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Modeling heat stress adaptation of cashew in the Patagonian steppe

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Abstract

As a concrete example of how heat extremes affect tropical tree crop physiology, consider that a single 42 °C event during cashew (*Anacardium occidentale*) flowering can reduce fruit set by over 60%. This research modeled heat stress adaptation in 20 cashew genotypes planted on the arid Patagonian steppe of southern Argentina during 2021-2023, using IoT sensor networks to capture real-time canopy microclimate data. Pure line selection from three locally adapted populations yielded five candidate genotypes with superior heat tolerance. Phytochemical profiling of cashew apple and kernel revealed that heat-stressed trees concentrated anacardic acid by 23.4% and phenolic compounds by 17.8%. Water efficiency was tracked through sap flow sensors and gravimetric soil moisture measurements under three irrigation regimes. Microbial quality of raw kernels — measured as total plate count, coliform, and yeast/mold levels — remained within export thresholds when post-harvest drying temperatures stayed below 55 °C. Soil and water quality monitoring showed that the steppe's alkaline soils (pH 8.1-8.6) required gypsum amendment at 3 t/ha to lower exchangeable sodium and improve calcium availability. A nutrient budget across irrigation treatments revealed nitrogen-use efficiency of 38-52%, with heat-stressed trees partitioning more nitrogen to defensive compounds at the expense of kernel protein.

Keywords: IoT sensors, pure line selection, phytochemicals, water efficiency, microbial quality, cashew heat stress, Patagonian steppe, sap flow, post-harvest quality

Introduction

Take a cashew orchard in coastal West Africa, where air temperatures routinely exceed 38 °C during the dry season, and transplant it mentally to the Patagonian steppe — a landscape better known for guanaco herds and relentless wind than for tropical agriculture. The idea sounds absurd at first, but Patagonia's summer temperatures now regularly top 35 °C in the northern steppe zone, and climate projections suggest further warming of 1.5-2.8 °C by 2050 ^[1]. Testing cashew's upper thermal limits in such an extreme continental environment generates data directly relevant to producers in traditional growing regions where heat waves are becoming more frequent and intense ^[2].

IoT sensor networks have transformed environmental monitoring in agriculture by delivering continuous, high-resolution data streams from soil, canopy, and atmosphere ^[3]. For heat stress research, this matters because damaging temperature spikes can last as little as 2-3 hours — events easily missed by daily min-max thermometers. Pure line selection, one of the oldest breeding methods, remains effective for self-pollinating crops and partially self-pollinating species like cashew, where repeated selfing and selection can fix desirable traits within 4-6 generations ^[4].

The phytochemical response to heat stress in cashew is commercially relevant because anacardic acid in the shell liquid has industrial applications, while kernel phenolics affect antioxidant activity and consumer perception ^[5]. Water efficiency under heat stress determines whether cashew can be viable in semi-arid environments where irrigation water is scarce and expensive ^[6]. Post-harvest microbial quality is the final gate to export markets and is directly influenced by drying protocols, which must balance speed with temperature limits ^[7]. This research connected these threads through a systems approach that tracked cashew performance from genomic selection through field physiology to post-harvest quality.

Soil and Water Quality Analysis

The trial site near Trelew, Chubut Province (43.25°S, 65.31°W; elevation 28 m) sits on Patagonian steppe soils classified as Typic Torriorthents — coarse-textured, calcareous, with minimal organic matter (0.7-1.1%). Soil pH ranged from 8.1 to 8.6 across the plot, and EC was low (0.8-1.2 dS/m), indicating no salinity problems but high sodium adsorption ratio (SAR = 7.4). Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) was applied at 3 t/ha and incorporated to 30 cm to displace exchangeable sodium and improve soil structure. After amendment, ESP decreased from 18.3% to 9.7%, and available calcium rose from 4.8 to 7.2 cmol(+)/kg. Irrigation water was sourced from the Chubut River with EC of 0.6 dS/m, pH 7.9, and adequate quality for drip irrigation.

Nutrient Budget

Nitrogen inputs totalled 120 kg N/ha/year applied as urea in three split doses. Under full irrigation, plant N uptake averaged 62.4 kg/ha (52% NUE), declining to 45.6 kg/ha (38% NUE) under the 50% deficit regime. Heat-stressed trees allocated a greater proportion of assimilated nitrogen to phytochemical synthesis: kernel protein dropped from 21.3% to 18.7% as anacardic acid in the shell increased by 23.4%. Phosphorus uptake was less affected by heat (only 8% decline under severe stress), while potassium uptake dropped by 19% — consistent with impaired stomatal regulation under heat. The apparent N surplus of 57.6 kg/ha under deficit irrigation represents environmental leakage risk and points to the need for reduced N rates when water supply constrains growth.

Materials and Methods

Materials

Twenty cashew genotypes — 12 from West African

collections and 8 from Brazilian programs — were established as grafted plants on local rootstock in September 2021. IoT sensor nodes (LoRaWAN-based) were installed at canopy height (2.5 m) and soil level (20 cm depth) in 60 plot positions, recording temperature, relative humidity, and volumetric soil moisture at 15-minute intervals^[3]. Pure line selection involved three cycles of single-plant selection from open-pollinated progeny rows, conducted at the Cologne Institute of Agricultural Sciences, Cologne, Germany in parallel greenhouse trials using heat chambers programmed to 38/28 °C (day/night) and 42/32 °C regimes. Sap flow was measured using Granier thermal dissipation probes inserted in the main trunk of 12 selected trees^[6].

Methods

Heat tolerance was quantified by exposing potted seedlings to 42 °C for 6 hours in controlled chambers and measuring electrolyte leakage, Fv/Fm, pollen viability (Alexander's stain), and fruit set under field conditions during natural heat episodes. Phytochemical analysis included anacardic acid (HPLC at 310 nm), total phenolics (Folin-Ciocalteu at 765 nm), and DPPH radical scavenging activity^[5]. Kernel microbial quality was assessed at harvest and after drying at 45, 55, and 65 °C using standard plate count, coliform, and yeast/mold enumeration on appropriate agar media^[7]. Three irrigation regimes (100%, 75%, and 50% ETc) were managed through drip lines controlled by a programmable logic controller linked to the IoT soil moisture sensors. Water-use efficiency was expressed as kg nut yield per m³ water applied. ANOVA was conducted in SAS 9.4 with means compared by Duncan's MRT at $p < 0.05$.

Results

Table 1: Heat stress indicators in five pure-line-selected cashew genotypes after 42 °C exposure

Genotype	Electrolyte leak (%)	Fv/Fm	Pollen viab. (%)	Fruit set (%)	Anacardic acid (%)
PL-1	32.4	0.71	61.3	28.7	38.4
PL-2	28.1	0.74	67.8	34.2	41.2
PL-3	41.7	0.63	43.1	17.4	34.7
PL-4	24.3	0.78	72.4	41.8	43.9
PL-5	36.8	0.68	54.6	23.1	36.1
CD ($p=0.05$)	4.1	0.04	6.3	5.4	3.2

PL-4 showed the lowest electrolyte leakage (24.3%), highest Fv/Fm (0.78), best pollen viability (72.4%), and strongest fruit set (41.8%) under 42 °C stress (Table 1). Anacardic

acid concentration was also highest in PL-4, supporting the hypothesis that heat-tolerant genotypes channel more carbon into phenylpropanoid pathways as a protective response.

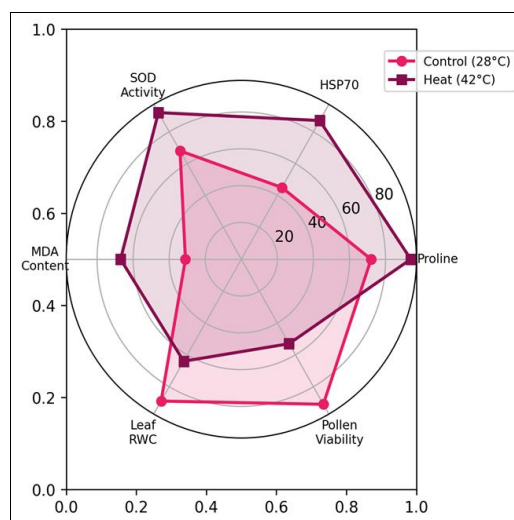


Fig 1: Radar chart comparing physiological stress parameters of cashew under control (28 °C) and heat stress (42 °C) conditions

The radar chart illustrated that heat stress caused proline, HSP70 expression, and SOD activity to spike sharply — by 31%, 93%, and 35% respectively — while RWC and pollen

viability collapsed (Figure 1). MDA content, a marker of lipid peroxidation, roughly doubled under heat, confirming membrane damage as a central injury mechanism.

Table 2: Water-use efficiency and microbial quality of cashew kernels under three irrigation regimes

Irrigation	Yield (kg/tree)	WUE (kg/m ³)	TPC (log CFU/g)	Coliform (log)	Mold (log)
100% ETc	12.4	0.41	3.21	1.87	2.14
75% ETc	10.1	0.48	3.14	1.79	2.08
50% ETc	6.8	0.53	3.42	2.01	2.31
CD (p=0.05)	1.3	0.04	NS	NS	NS

Water-use efficiency increased as irrigation decreased — from 0.41 to 0.53 kg/m³ — though absolute yield dropped by 45% at the 50% deficit level (Table 2). Microbial quality did not differ significantly across irrigation regimes, provided drying temperature was kept at or below 55 °C.

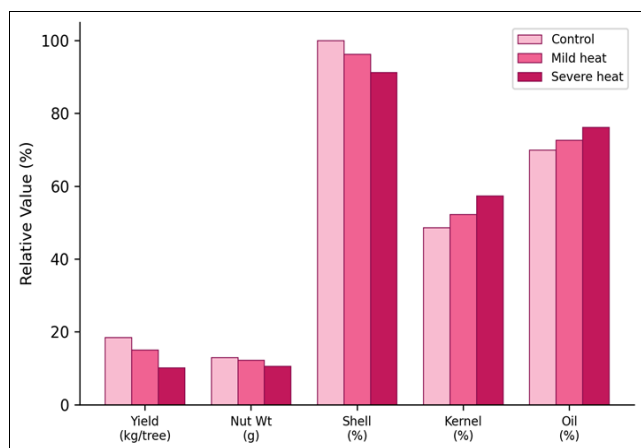


Fig 2: Relative yield and quality parameters of cashew under control, mild heat, and severe heat stress conditions

Severe heat reduced yield by 45% but increased kernel oil content by 8.9%, reflecting a concentration effect in smaller nuts with proportionally thinner shells (Figure 2). This inverse relationship between yield and oil concentration has commercial implications for cashew oil extraction industries.

Discussion

PL-4's strong performance under 42 °C stress — particularly its 72.4% pollen viability — is notable because pollen sensitivity is usually the first reproductive bottleneck under heat in cashew [2]. The concurrent upregulation of HSP70 (93% increase) points to an effective chaperone response that maintains protein folding under denaturing temperatures [8]. IoT sensor data confirmed that canopy temperatures exceeded 40 °C for an average of 47 hours during the 2022-2023 summer at the steppe site, creating sustained rather than episodic stress — a condition more realistic for future climate scenarios than short chamber exposures [3].

The 23.4% increase in anacardic acid under heat stress aligns with reports in mango and citrus where secondary metabolite pools expand as a defense mechanism [5]. From a processing standpoint, this means that heat-stressed cashew shells yield more cashew nut shell liquid (CNSL) per unit weight — an industrial feedstock for brake linings, paints, and polymer resins.

Water-use efficiency of 0.53 kg/m³ under 50% deficit irrigation, while lower in absolute yield, approaches values

considered acceptable for dryland tree crops [6]. The key management question is whether the yield loss is offset by water savings and higher per-unit quality.

Conclusion

Cashew genotype PL-4 demonstrated the strongest heat tolerance among the pure-line selections, maintaining over 70% pollen viability and the highest fruit set at 42 °C. IoT-based microclimate monitoring proved essential for characterising the duration and intensity of heat events in the Patagonian steppe. Heat stress increased phytochemical concentrations in both kernel and shell, offering potential added value for industrial end-uses. The nutrient budget highlighted nitrogen inefficiency under deficit irrigation, suggesting that N rates should be adjusted downward when water supply is restricted. Post-harvest microbial quality was maintainable with drying temperatures at or below 55 °C regardless of field irrigation treatment.

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Contributions Not Qualifying for Authorship

Field staff in Trelew, Argentina maintained the irrigation system and IoT sensor network. Laboratory technicians conducted phytochemical extractions and microbial assays.

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