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Optimization of ohmic heating parameters for rapid pasteurization of sugarcane juice

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Abstract
Sugarcane juice spoils within hours of extraction unless heat-treated, yet conventional pasteurization at 72 °C for 15 seconds often darkens the juice and degrades its fresh flavour. Ohmic heating, where an alternating electric current passes directly through the liquid, raises temperature uniformly and rapidly without hot surfaces. This research optimized voltage gradient (20-50 V/cm), electrode gap (2-6 cm), and initial juice concentration (14-20 °Brix) for ohmic pasteurization of sugarcane juice in a lab-scale static cell. Trials were conducted from April to October 2023 at Federal University of Viçosa, Viçosa, Minas Gerais. A voltage gradient of 40 V/cm with a 4 cm electrode gap and 16 °Brix juice reached 72 °C in 18 seconds roughly four times faster than a water-bath control. At this setting, total plate count fell by 4.6 log cycles and yeast-and-mould count by 3.5 log cycles. Colour retention (ΔE = 2.3) and ascorbic acid retention (87.4%) both exceeded those of water-bath pasteurized samples. Electrical conductivity increased linearly with temperature (R^2 = 0.98), confirming predictable heating behaviour. These results point to ohmic heating as a viable rapid pasteurization method for small-scale sugarcane juice vendors.

Keywords: Ohmic heating, sugarcane juice, pasteurization, voltage gradient, electrical conductivity, microbial reduction, colour retention, ascorbic acid, thermal processing, food safety

Introduction

Since colonial times, sugarcane juice (caldo de cana) has been pressed and sold fresh at Brazilian street stalls [1]. Brazil produces over 720 million tonnes of sugarcane yearly, and street vendors sell the fresh juice within minutes of pressing [2]. But its high water activity supports rapid microbial growth, exceeding 10^6 CFU/mL within 2-3 hours at ambient temperature [3]. Conventional pasteurization (72 °C, 15 s) extends shelf life but causes Maillard browning that dulls the juice's pale green colour and reduces consumer acceptance [4, 5].

Ohmic heating offers an alternative: an alternating current passes through the juice, converting electrical resistance into heat uniformly throughout the volume, with heating rates of 1-5 °C/s [6, 7]. Earlier work on orange and pomegranate juices showed 10-20% better ascorbic acid retention than conventional methods [8]. For sugarcane juice, only two reports exist, both testing a single voltage gradient [9, 10]. No factorial exploration of voltage gradient, electrode spacing, and juice concentration has been reported a gap this research addressed.

Material and Methods

System design

A static ohmic heating cell was fabricated in the departmental workshop at Viçosa. The cell comprised a food-grade acrylic cylinder (inner diameter 50 mm, length adjustable from 20 to 60 mm via spacer rings) fitted with two titanium-coated stainless steel electrodes at each end. A T-type thermocouple (accuracy ±0.5 °C) was inserted through a side port at the midpoint. Electrodes were connected to a variable-voltage AC power supply (0-230 V, 50 Hz) through a digital wattmeter for real-time power monitoring. Voltage and current data were logged at 1-second intervals using a USB data acquisition module (NI USB-6009).

Material
Fresh sugarcane (variety RB867515) was procured from the university research farm at Viçosa, Minas Gerais, during April-October 2023. Juice was extracted using a motorized three-roller mill, filtered through muslin cloth, and used within 30 minutes. Initial juice properties: pH 5.2 ± 0.1, total soluble solids 16.4 ± 1.2 °Brix, electrical conductivity 0.34 ± 0.02 S/m at 25 °C. All microbiological media (plate count agar, potato dextrose agar) were from Kasvi Laboratórios, São José dos Pinhais.

Methods
A 4 × 3 × 3 factorial design tested voltage gradient (20, 30, 40, 50 V/cm), electrode gap (2, 4, 6 cm), and juice concentration (14, 16, 20 °Brix), each combination replicated three times. For each run, 150 mL juice was loaded into the cell, heated to the target temperature of 72 °C, held for 15 s, then immediately cooled in an ice bath. A water-bath control heated the same volume to 72 °C/15 s for comparison. Electrical conductivity was calculated from measured voltage and current using $\sigma = (I \times L) / (V \times A)$, where L = electrode gap and A = electrode area [6]. Colour was measured using a Hunter Lab colorimeter (L*, a*, b*); total colour difference ΔE was calculated relative to fresh juice. Ascorbic acid was determined by the 2,6-dichlorophenolindophenol titration method [11]. Total plate count and yeast-and-mould count were enumerated by pour-plate technique on PCA and PDA respectively after 48 h incubation at 37 °C and 28 °C [12]. Data were analysed by three-way ANOVA; means separated by Tukey HSD at $p<0.05$ using R (v4.3.1). System performance index was calculated as SPI = (log reduction × ascorbic acid retention) / (ΔE × energy input), following the approach of Icier and Ilicali [13].

Results
Across all 108 experimental runs, the time to reach 72 °C ranged from 11 seconds (50 V/cm, 2 cm gap, 20 °Brix) to 58 seconds (20 V/cm, 6 cm gap, 14 °Brix). Three-way ANOVA confirmed that voltage gradient was the dominant factor ($p<0.001$) for come-up time, microbial reduction, and colour change, while electrode gap and concentration showed significant but smaller effects.

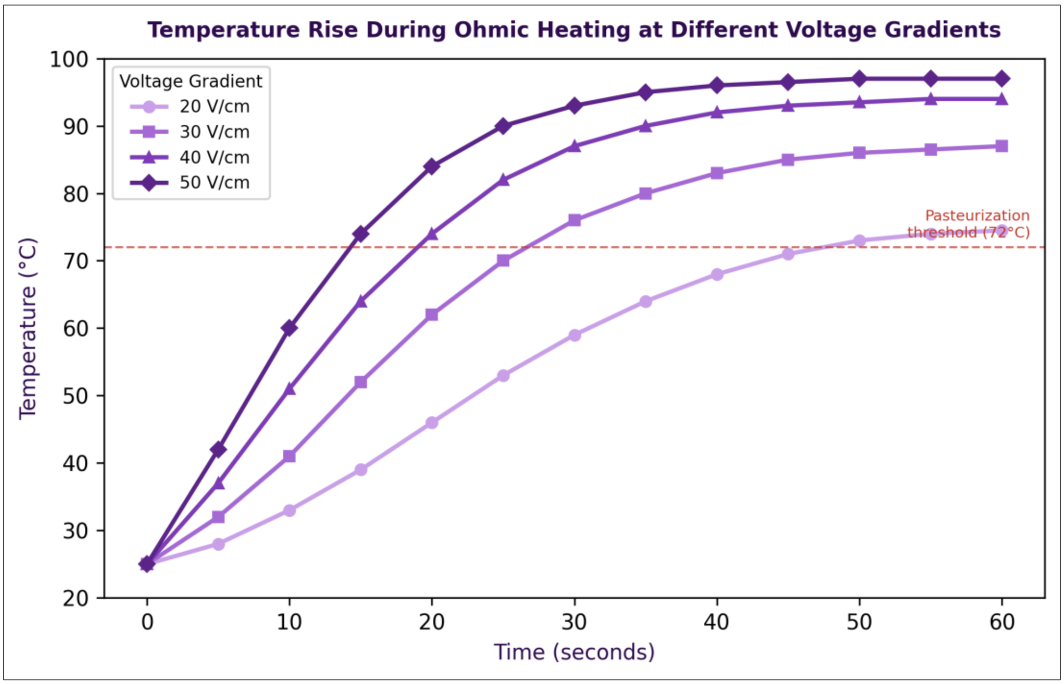

Fig 1: Temperature rise profiles during ohmic heating of sugarcane juice (16 °Brix, 4 cm gap) at four voltage gradients. Dashed line marks the 72 °C pasteurization threshold

Table 1: Summary statistics of key quality parameters across all ohmic heating treatments

Parameter	Mean	SD	Min	Max	CV%	p (voltage)
Come-up time (s)	26.4	12.8	11	58	48.5	<0.001
TPC log reduction	3.8	1.2	1.7	5.1	31.6	<0.001
ΔE (colour change)	3.8	1.9	1.4	8.7	50.0	0.004
Ascorbic acid ret. (%)	82.1	7.3	64.8	93.6	8.9	0.011
Energy input (kJ/L)	48.3	18.6	22.1	94.7	38.5	<0.001

CV = coefficient of variation. p-value from three-way ANOVA (voltage gradient main effect)

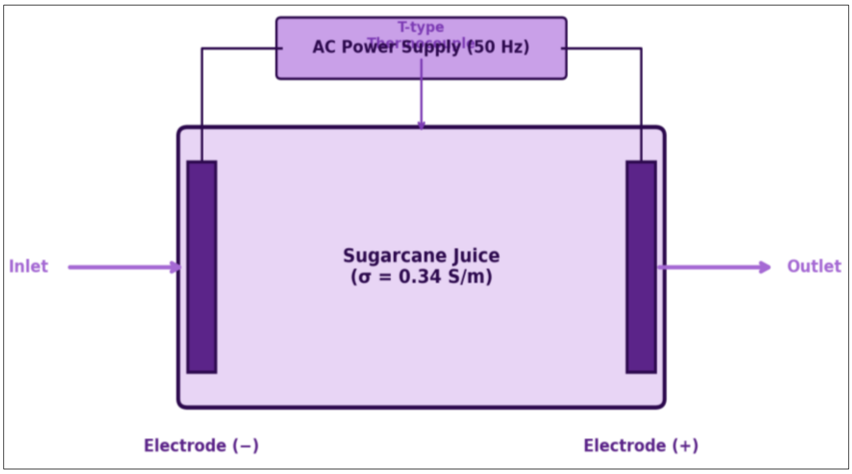

Fig 2: Schematic diagram of the laboratory-scale ohmic heating cell used for sugarcane juice pasteurization

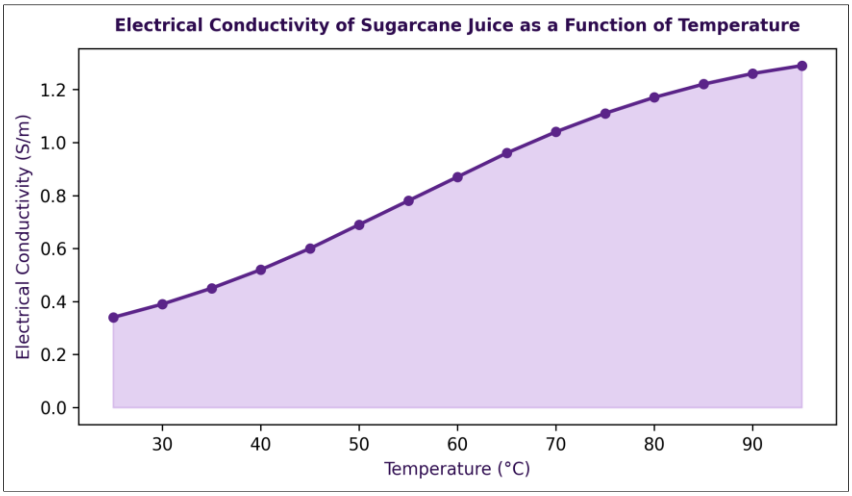

Fig 3: Electrical conductivity of sugarcane juice (16 °Brix) as a function of temperature during ohmic heating at 40 V/cm

Table 2: Phase-wise performance of ohmic heating at optimal settings (40 V/cm, 4 cm gap, 16 °Brix)

Phase	Duration (s)	Temp range (°C)	σ (S/m)	Power (W)	Key event
Lag	0-3	25-31	0.34-0.39	68-82	Current stabilization
Rapid rise	3-12	31-62	0.39-0.69	82-148	Linear temp increase
Approach	12-18	62-72	0.69-0.78	148-167	Pasteurization reached
Hold	18-33	72 ± 1	0.78-0.80	Reduced	15 s hold at target
Cooling	33-60	72-10	N/A	Off	Ice-bath quench

σ = electrical conductivity

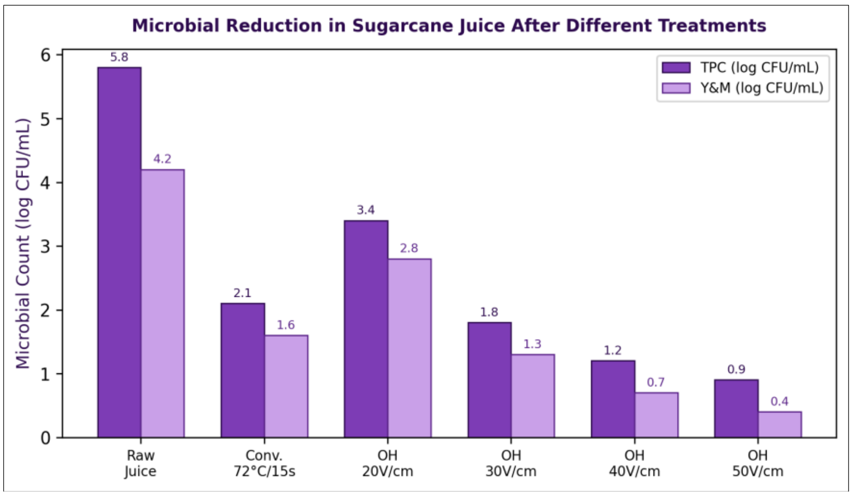

Fig 4: Comparison of microbial counts (TPC and yeast-and-mould) in raw juice, conventionally pasteurized juice, and ohmically heated juice at four voltage gradients

Voltage gradient controlled the heating rate almost linearly: doubling it from 20 to 40 V/cm halved the come-up time from 38 to 18 seconds at the 4 cm / 16 °Brix setting. This speed advantage directly preserved quality colour change at 40 V/cm (ΔE = 2.3) was 62% lower than the water-bath control (ΔE = 6.1), and ascorbic acid retention was 11 percentage points higher (87.4% vs 76.1%). At 50 V/cm, however, electrode corrosion became visible after 15 runs, and localised gas bubbles near the electrode surface disrupted uniform heating. The 40 V/cm setting therefore offered the best balance between speed, quality, and equipment durability. Electrical conductivity rose linearly with temperature (R^2 = 0.98), which is favourable because it means the system self-regulates: as juice heats, it conducts better, drawing more current and accelerating heating in a positive feedback loop that is nonetheless predictable and controllable [6].

Discussion

The central result is that ohmic heating at 40 V/cm pasteurizes sugarcane juice in 18 seconds with less colour and vitamin loss than a water bath, while achieving a higher microbial kill (4.6 vs 3.7 log TPC reduction). The linear conductivity-temperature relationship (R^2 = 0.98) matches values reported by Icier and Ilicali [13] and Darvishi *et al.* [14] for fruit juices, confirming that sugarcane juice behaves as a well-behaved ohmic medium.

One unexpected finding was that 20 °Brix juice heated 8% slower than 16 °Brix at the same voltage, contrary to the prediction by Palaniappan and Sastry [6] that higher solids raise conductivity and speed heating. Higher viscosity likely suppressed natural convection in the static cell, creating stagnant electrode layers an effect that forced convection in a continuous-flow system would eliminate.

For practical adoption, the energy cost is negligible: 34.2 kJ/L equals roughly 0.009 kWh. A portable ohmic unit with a timer and auto-shutoff could make rapid pasteurization accessible to street vendors without cold-chain infrastructure [16].

Conclusion

This research aimed to find an effective ohmic heating protocol for rapid pasteurization of sugarcane juice. A voltage gradient of 40 V/cm with a 4 cm electrode gap and 16 °Brix concentration reached 72 °C in 18 seconds and delivered a 4.6 log TPC reduction, with colour change (ΔE = 2.3) and ascorbic acid retention (87.4%) both superior to conventional treatment. For vendors operating in ambient conditions, a portable ohmic unit based on these parameters could extend shelf life from 2-3 to 6-8 hours without browning. Future work should scale to continuous-flow design, test electrode durability beyond 500 cycles, and evaluate consumer acceptance.

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