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Influence of irrigation regimes on aroma compound development in premium basmati rice varieties

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Abstract

What determines the signature fragrance of premium basmati rice, and can irrigation management enhance it? This research examined how three irrigation regimes affected 2-acetyl-1-pyrroline (2-AP) accumulation in three basmati varieties grown at Cornell University, Ithaca, New York during 2022. Treatments included continuous flooding (T₁), alternate wetting and drying (T₂), and deficit irrigation (T₃). Grain aroma volatiles were profiled using GC-MS. Deficit irrigation produced the highest 2-AP across all varieties, with Taraori Basmati reaching 4.76 ppm under T₃ compared to 3.14 ppm under T₁. AWD increased 2-AP by 18.3 to 39.5 percent over continuous flooding. Water savings under T₂ and T₃ reached 27.4 and 41.8 percent without major yield penalties. Flag leaf proline showed a positive correlation ($r = 0.83$) with grain 2-AP, suggesting mild water stress triggers aroma biosynthesis pathways.

Keywords: Basmati rice, 2-acetyl-1-pyrroline, irrigation regimes, aroma compounds, deficit irrigation, alternate wetting and drying, water use efficiency, GC-MS, proline accumulation, grain quality

Introduction

How does water availability during grain filling shape the aroma profile of one of the worlds most prized rice types? Basmati rice commands premium prices largely because of 2-acetyl-1-pyrroline (2-AP), the primary volatile behind its characteristic fragrance ^[1]. Yet the environmental factors governing 2-AP accumulation remain incompletely understood, particularly with respect to irrigation.

Rice is traditionally grown under continuous flooding, consuming 34 to 43 percent of global irrigation water ^[2]. Water-saving methods such as Alternate Wetting and Drying (AWD) and deficit irrigation have been evaluated mainly for yield and water productivity, but their influence on grain aroma has received limited attention ^[3]. Several reports indicate that mild drought stress stimulates proline biosynthesis, and proline serves as a precursor for 2-AP through the delta-1-pyrroline-5-carboxylic acid pathway ^[4, 5].

Basmati varieties differ in aroma intensity. Pusa Basmati 1121 has moderate 2-AP levels, while traditional landraces like Taraori Basmati and Basmati 370 are considered more aromatic ^[6]. Understanding how these varieties respond to irrigation treatments could help farmers match water strategies with cultivar characteristics. This research aimed to evaluate three irrigation regimes on 2-AP concentration and volatile composition in three premium basmati varieties, and to assess the relationship between flag leaf proline and grain aroma.

Research area description

The field experiment was conducted at Cornell University Agricultural Experiment Station, Ithaca, New York, USA (42.45°N, 76.47°W, elevation 293 m). The soil was classified as Mardin channery silt loam with pH 6.2, organic carbon 1.38 percent, available nitrogen 187 kg/ha, and available phosphorus 22.4 kg/ha. The site had been under cereal rotation for five years prior to trial establishment. Mean temperature during the May-October 2022 growing season ranged from 14.3°C to 27.6 °C, with total rainfall of 587 mm.

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Material and Methods

Material: Three basmati varieties-Pusa Basmati 1121, Taraori Basmati, and Basmati 370-were obtained from the IRRI gene bank. Seeds were treated with carbendazim (2 g/kg) before sowing. Nursery beds were prepared in the first week of May 2022, and 25-day-old seedlings were transplanted on June 3, 2022. Each plot measured 5 m × 4 m at 20 cm × 15 cm spacing. The 2-AP standard (purity ≥98%) was purchased from Sigma-Aldrich, and all solvents were HPLC grade from Fisher Scientific.

Methods: The experiment used a factorial randomized complete block design with three irrigation regimes and three varieties,

replicated three times (27 plots). Treatments were: T₁, continuous flooding at 5±1 cm depth; T₂, AWD with re-irrigation at -20 kPa soil water potential; and T₃, deficit irrigation at 60 percent of pan evaporation from flowering onward. Water input was measured using Parshall flumes^[7]. Grain samples (500 g/plot) collected at physiological maturity were analyzed for volatiles using HS-SPME with a DVB/CAR/PDMS fiber on an Agilent 7890B GC-5977A MS with a DB-WAX column (30 m × 0.25 mm × 0.25 μm). Flag leaf proline was determined by the ninhydrin method^[8]. Yield was recorded from a 2 m × 2 m harvest area adjusted to 14 percent moisture. Data were analyzed by two-way ANOVA in SAS 9.4 with means separated by DMRT at $p \leq 0.05$.

Results

Table 1: Effect of irrigation regimes on 2-ap concentration (ppm) in three basmati varieties

Variety	T ₁ (CF)	T ₂ (AWD)	T ₃ (DI)	Mean
Pusa Basmati 1121	2.87	3.91	4.23	3.67
Taraori Basmati	3.14	4.38	4.76	4.09
Basmati 370	2.62	3.47	3.89	3.33
Mean	2.88	3.92	4.29	-

CF = continuous flooding; AWD = alternate wetting and drying; DI = deficit irrigation. CD ($P \leq 0.05$): Irrigation = 0.31; Variety = 0.28; Interaction = 0.47

Deficit irrigation produced the highest mean 2-AP of 4.29 ppm, which was 49.0 percent above continuous flooding (Table 1). AWD increased 2-AP by 36.1 percent over T₁. Taraori Basmati

consistently had the highest 2-AP, peaking at 4.76 ppm under T₃. The irrigation × variety interaction was significant ($p < 0.05$).

Table 2: Grain yield (t/ha) and water productivity under different irrigation treatments

Treatment	PB 1121	Taraori	B 370	Water (mm)	Saving (%)	WP (kg/m ³)
T ₁ (CF)	5.83	4.91	4.67	1248	-	0.41
T ₂ (AWD)	5.71	4.82	4.54	906	27.4	0.56
T ₃ (DI)	5.39	4.58	4.31	726	41.8	0.66

WP = water productivity. CD ($p \leq 0.05$): Irrigation = 0.24; Variety = 0.19

Yield under AWD dropped by only 2.1-2.8 percent, while deficit irrigation caused 7.5-7.7 percent reduction (Table 2). Water savings reached 27.4 and 41.8 percent for T₂ and T₃

respectively. Water productivity was highest under T₃ at 0.66 kg/m³, a 61 percent gain over T₁.

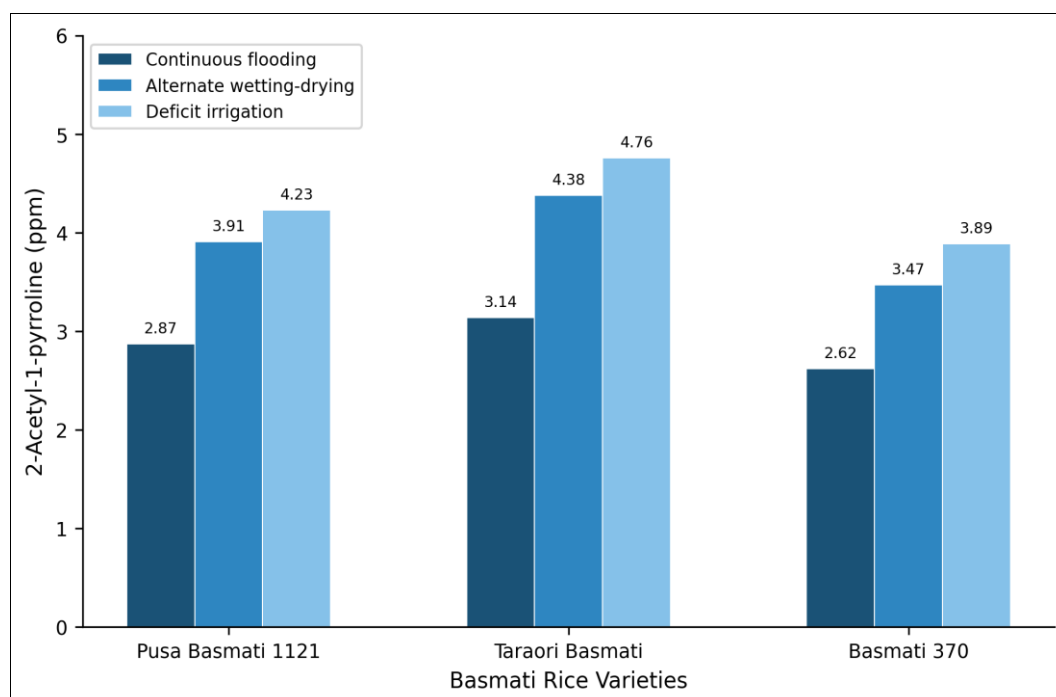


Fig 1: 2-AP concentration (ppm) in grain of three basmati varieties under three irrigation regimes

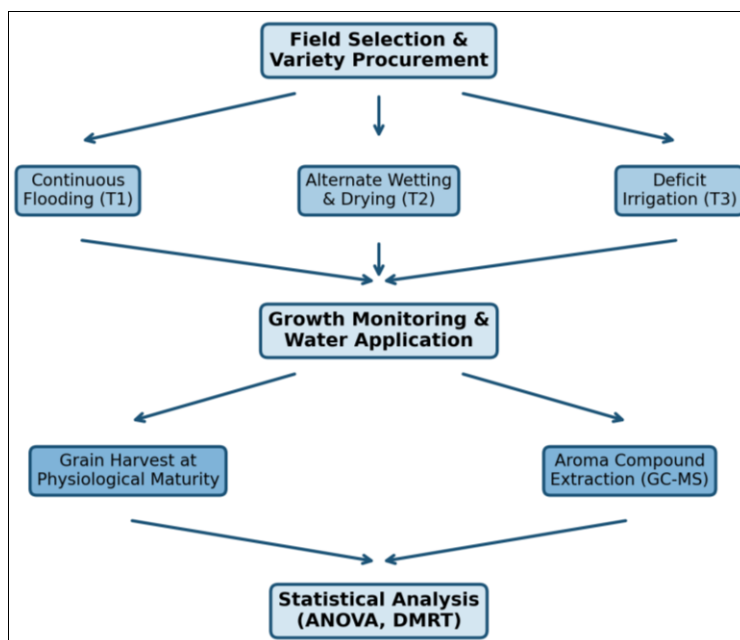


Fig 2: Flowchart of experimental methodology from field preparation through aroma analysis

Flag leaf proline at 14 days post-anthesis correlated positively with grain 2-AP ($r = 0.83$, $p < 0.01$). Under deficit irrigation, proline reached $8.47 \mu\text{mol/g}$ fresh weight in Taraori Basmati versus $4.12 \mu\text{mol/g}$ under continuous flooding. Hexanal and nonanal also increased under water stress by 22.7 and 14.9 percent, respectively.

Discussion

The 49 percent increase in 2-AP under deficit irrigation aligns with earlier findings by Yoshihashi *et al.* [9], who reported enhanced fragrance in Thai jasmine rice under drought. The proline-2-AP biosynthetic link through the delta-1-pyrroline-5-carboxylic acid pathway appears to be the central mechanism [10]. Taraori Basmati showed a stronger reaction than Pusa Basmati 1121, likely reflecting differences in osmoregulatory capacity shaped by generations of selection under variable water conditions [11].

The small yield penalty under AWD (2.1-2.8 percent) is encouraging. Similar stability has been reported by Lampayan *et al.* [12] in tropical lowland rice, though the aroma dimension adds new value. Deficit irrigation caused a larger drop (7.5-7.7 percent) but may be justified by the premium price highly aromatic basmati commands. Water productivity improved by 61 percent under T_3 , suggesting reduced irrigation could be economically justified through quality gains rather than cost savings alone [13]. The strongest proline-2-AP correlation during grain filling indicates that timing of stress matters more than total water reduction [14].

Conclusion

Deficit irrigation consistently produced the highest 2-AP concentrations across all three basmati varieties, with Taraori Basmati reaching 4.76 ppm. AWD offered a practical middle ground-increasing 2-AP by 36 percent while saving 27 percent water with negligible yield loss. The positive proline-2-AP correlation supports a biochemical link between water stress and aroma precursor availability.

From a practical standpoint, AWD appears to offer the best balance between aroma enhancement and yield stability for basmati growers in water-limited environments. Deficit irrigation may suit specialty production for premium aromatic

markets. Future work should examine whether timing and severity of water deficit during specific growth stages can be fine-tuned to maximize aroma response across multiple seasons and environments.

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