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Integrated organic–mineral nutrient management enhances flowering, fruit retention and yield of avocado cv. TKD-1 under high-density planting in Tamil Nadu

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Abstract

The low and erratic productivity of avocado (*Persea americana* Mill.) is primarily constrained by excessive flower and fruit abscission. In the present study, integrated organic–mineral nutrient management significantly influenced flowering behaviour and fruit-bearing efficiency of 12-year-old avocado cv. TKD-1 grown under high-density conditions in Tamil Nadu. The application of compost (25 kg tree^{-1}) + 50% potassium through polyhalite and 50% phosphorus through phosphorus-rich organic manure (PROM) outperformed the other nine nutrient treatments in all flowering and fruiting efficiency attributes. In addition to producing the greatest number of determinate (93.34) and indeterminate inflorescences (407.56), the earliest flowering (25.33 days), the greatest number of flowers per inflorescence (195.34) and larger inflorescences (8.45 cm length and 13.45 cm width), this treatment also minimised flower drop (90.49%). Reduced early (59.98%) and summer fruit drop (40.02%), higher fruit set (9.51%), maximum fruit retention (24.00%) and maximum yield (352.54 kg) all demonstrated a significant improvement in fruit-bearing efficiency. Consequently, the control group's yield (109.26 kg tree^{-1}) and fruit retention (14.02%) were the lowest. The combined application of organic and mineral nutrient sources improved the reproductive efficiency of avocado cv. TKD-1 under high-density orcharding by enhancing flowering synchronisation, fruit set, fruit retention and yield. However, the findings are based on a single location and one cropping season; therefore, further validation across multiple locations and seasons is required before making broader recommendations.

Introduction

Avocado, popularly known as the butter fruit, alligator pear, dog fruit, future fruit, divine fruit, functional fruit and super fruit, is highly valued for its exceptional nutritional and antioxidant properties [1]. The complex flowering biology and low reproductive efficiency are among the major causes of low and inconsistent productivity in avocado. Effective fruit set rarely surpasses the thousands of flowers produced by a mature avocado tree, leading to significant reproductive losses at various developmental stages [2,3]. One of the main biological bottlenecks limiting yield stability under various agroclimatic conditions is this low conversion efficiency. In avocado, both determinate and indeterminate inflorescences develop on the terminals of the previous season's growth [1]. Determinate inflorescences terminate in flowers without further vegetative growth, whereas indeterminate inflorescences retain a vegetative apex and continue shoot growth during and after flowering. Consequently, competition for photoassimilates between developing shoots, flowers and young fruitlets is greater in indeterminate inflorescences because of the continued vegetative growth [4,5]. This source-sink competition decreases fruit retention and final yield by speeding up flower abscission and early fruit drop [6,7]. Avocado's distinct flowering biology, protogynous diurnally synchronous dichogamy, limits effective self-pollination and necessitates precise temporal overlap between male and female phases for successful fertilisation, further limiting reproductive success [8,9].

Fluctuations in environmental conditions during the flowering season, especially temperature and water, affect the receptivity of the stigma, viability of pollen and growth of pollen tubes, thus contributing to increased flower drop and poor fruit set [10]. Even after fertilization, physiological fruit drop commonly occurs due to limited carbohydrate availability and hormonal imbalances during early fruit development. The reduced fruit drop observed in the present study could reflect improved carbohydrate status and hormonal balance [11]. High-density orchards are more productive per unit area but are more prone to nutrient stress due to intense root competition and smaller rhizosphere volume. High density leads to quick depletion of necessary macro- and secondary nutrients (N, P, K, Ca, Mg, S) in the soil and root interlocking hinders efficient nutrient uptake, causing nutrient imbalance. High-density canopies also affect soil microclimate and microbial populations, reducing nutrient use efficiency. Such imbalances may hinder flowering, fertilization and fruitlet retention, leading to increased flower and fruit abscission. The reduced fruit drop observed in the present study may be associated with improved abscission-zone integrity; hence, careful and balanced nutrient application is required to maintain reproductive function and soil fertility in high-density orchards (Lahav and Gazit, 1994). Conventional fertilization practices do not always provide a proper balance between nutrient application and the peak reproductive phase; hence, assimilate competition between the vegetative and reproductive sinks is further intensified. Integrated organic-mineral nutrient management practices can improve nutrient availability, soil biological activity and provide a continuous supply of assimilates during the flowering and early fruit growth phases.

Although integrated nutrient management has been widely investigated in several horticultural crops, information on the combined application of polyhalite, phosphorus-rich organic manure (PROM) and compost in avocado under Indian high-density orchard systems remains limited. Therefore, the present study was undertaken to evaluate their influence on flowering behaviour, fruit retention and yield of avocado cv. TKD-1 under high-density planting conditions.

Materials and Methods

Experimental site

The field experiment was carried out at Pandrimalai, Dindigul district, Tamil Nadu, India (1251 m above mean sea level), in the Western Agro-Climatic Zone of Tamil Nadu. The experimental location has a subtropical climate with an average annual rainfall of about 800 mm, mainly received during the North-East Monsoon season (October to December). The average annual temperature during the period of experimentation varied from 15 to 29°C. Meteorological information for the period of the experiment was collected from the Office of the Assistant Director of Statistics, Dindigul.

Experimental design

The experiment was conducted during the 2024–2025 cropping season and observations were recorded during one flowering and fruiting cycle. The experiment was conducted on 12-year-old avocado (*Persea americana* Mill.) cv. TKD-1 trees planted at 5 × 5 m spacing (400 trees ha^{-1}), which is considered a high-density planting system under Indian conditions compared with the conventional spacing of 8 × 8 m to 10 × 10 m (100–156 trees ha^{-1}). The study was laid out in a Randomized Block Design (RBD) with 10 treatments, three replications, and 10 trees per replication, comprising a total of 300 experimental trees.

Statistical analysis

The statistical analysis was done as per the methods described by Panse and Sukhatme [12]. Five representative trees were sampled within each replication and the mean value of these trees was considered as one experimental unit for statistical analysis. The experiment was analyzed using Analysis of Variance (ANOVA) appropriate for a Randomized Block Design (RBD). Observations recorded from five representative trees in each replication were averaged and considered as one experimental unit for analysis. Treatment means were compared using the Critical Difference (CD) test at the 5% level of significance. Statistical analysis was performed using R software.

Nutrient management: Avocado is a nutrient-demanding crop and grows well when given a balanced ratio of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O Fertilizers were applied in two equal soil-applied splits during August (pre monsoon) and January (post monsoon) within the tree basin, followed by uniform irrigation. The experiment was conducted to assess per tree nutrient management using integrated organic-mineral fertilizers, namely compost (25 kg $tree^{-1}$), 50% polyhalite (1.42 kg $tree^{-1}$) and 50% phosphorus-rich organic manure (0.52 kg $tree^{-1}$ ha-1), compared with 100% recommended dose of fertilizers (RDF) consisting of urea (1.73 kg), single super phosphate (1.31 kg) and muriate of potash (0.66 kg) per tree, containing 800:210:400 g $N:P_2O_5:K_2O$ $tree^{-1}$. Polyhalite contains 14% K_2O (11.6% K), 17% CaO (12.2% Ca), 6% MgO (3.6% Mg) and 48% SO_3 (19.2% S). PROM (Phosphate Rich Organic Manure) is a composted product of rock phosphate (32 ± 2% P_2O_5) with organic matter and it contains ~ 20% available P, along with 1.9–2.5% N, 2.5–3.4% K, 3.0–4.0% Ca, 0.8–1.5% Mg and 1.0-1.5% S, plus trace Fe and Zn. The compost contained 1.45% total nitrogen (N), 0.85% phosphorus (P_2O_5), 1.20% potassium (K_2O), and 18.60% organic carbon, with a C:N ratio of 12.8:1. Standard orchard management practices, including pruning, and plant protection, were uniformly maintained across all treatments using healthy, uniformly bearing trees. Flowering, fruit set, fruit drop and yield observations were recorded using standard horticultural procedures, and fruits were harvested at physiological maturity in a single harvest.

Table 1
Key Soil Characteristics of the Experimental Plot

Soil texture	**Sandy clay loam**
Bulk density (g cm^{-3})	1.45
Porosity (%)	45.28
Maximum water holding capacity (%)	48.50
Soil pH (1:2 soil:water)	5.71
EC (dS m^{-1} at 25°C)	0.32
Organic carbon (%)	1.17
Available nitrogen (kg ha^{-1})	398.23
Available phosphorus (kg ha^{-1})	24.60
Available potassium (kg ha^{-1})	123.90

Assessment of Flowering, Fruit Set and Fruit Retention

The number of flowers produced per tree was recorded during the flowering period. Fruit set was assessed by counting the number of fruits formed after anthesis. Flower drop, early fruit drop, summer fruit drop, and fruit retention were calculated using the following formulae

1. Fruit Set (%) = (Number of fruits set / Total number of flowers) × 100
2. Flower Drop (%) = [(Total flowers – Fruits set) / Total flowers] × 100
3. Early Fruit Drop (%) = [(Initial fruit set – Fruits retained after early drop) / Initial fruit set] × 100
4. Summer Fruit Drop (%) = [(Fruits retained after early drop – Fruits harvested) / Fruits retained after early drop] × 100
5. Fruit Retention (%) = [1 - early fruit drop/100] x [1 - summer fruit drop/100] x 100

Results and Discussion

Days taken to initiation of flowering

Flowering attributes of avocado cv. TKD-1 differed significantly among treatments (Table 2), with integrated organic–mineral nutrition proving superior. Treatment T_9 (25 kg Compost + 50% K through Polyhalite + 50% P through PROM) induced the earliest flowering (25.33 days), significantly earlier than the control (34.14 days). The improved performance may be associated with enhanced nutrient availability and assimilate partitioning resulting from the potassium supplied through polyhalite, which facilitate carbohydrate transport, osmotic adjustment, enzyme activation and floral primordia differentiation, thereby promoting an earlier transition from the vegetative to the reproductive phase [13–15]. These responses attributed to the complementary supply of K, Ca, Mg, S and P through polyhalite, PROM and compost, which improve nutrient availability and support ATP-mediated energy metabolism and meristematic functions during floral induction [16–18]. Unlike Single Super Phosphate (SSP), which is readily fixed as Fe- and Al-phosphates in acidic soils, organic forms of P like PROM have higher plant-available P, which is solubilized by microorganisms and recycled in the soil, thus favoring better P use efficiency and soil fertility even under low-input agriculture [19–21].

Table 2
Organic–mineral nutrient management and flowering response in avocado cv. TKD-1

Treatment Details	Days taken to initiation of flowering	No. of determinate inflorescences	No. of indeterminate inflorescences	No. of flowers/ inflorescence	Inflorescence length (cm)	Inflorescence width (cm)	Flower drop (%)
T_1	32.18[e]	90.07[e]	402.81[e]	168.28[e]	6.29[e]	10.37[e]	93.74[e]
T_2	30.63[d]	90.8[d]	403.89[d]	174.40[d]	6.78[d]	11.07[d]	93.00[d]
T_3	28.77[c]	91.70[c]	405.18[c]	181.76[c]	7.37[c]	11.91[c]	92.12[c]
T_4	30.35[d]	90.94[d]	404.08[d]	175.49[d]	6.87[d]	11.19[d]	92.87[d]
T_5	27.03[b]	92.53[b]	406.38[b]	188.62[b]	7.91[b]	12.69[b]	91.30[b]
T_6	27.32[b]	92.39[b]	406.18[b]	187.48[b]	7.82[b]	12.56[b]	91.43[b]
T_7	28.90[c]	91.63[c]	405.08[c]	181.21[c]	7.32[c]	11.84[c]	92.19[c]
T_8	25.64[a]	93.19[a]	407.34[a]	194.10[a]	8.35[a]	13.31[a]	90.64[a]
T_9	25.33[a]	93.34[a]	407.56[a]	195.34[a]	8.45[a]	13.45[a]	90.49[a]
T_{10}	34.14[f]	89.13[f]	401.45[f]	160.52[f]	5.67[f]	9.49[f]	94.67[f]
S.Ed.	0.59	0.28	0.41	2.32	0.19	0.26	0.28
C.D. @ 5%	1.23	0.59	0.86	4.87	0.39	0.55	0.59

T_1- 100% RDF, T2–50% RDF + 25 kg compost, T_3 – 50% RDF + 50% K through Polyhalite, T_4 – 50% RDF + 50% P through PROM, T_5 – 50% K through Polyhalite + 50% P through PROM, T_6 – 25 kg compost + 50% K through Polyhalite, T_7 – 25 kg compost + 50% P through PROM, T_8 – 50% RDF + 50% K through Polyhalite + 50% P through PROM, T_9 – 25 kg compost + 50% K through Polyhalite + 50% P through PROM, T_{10} - Control. Treatments with the same letter grouping are not significantly different.

No. of determinate, indeterminate inflorescence and flowers per inflorescence

Significant differences in inflorescence formation for avocado cv. TKD-1 (Table 2) were evident among treatments, with T_9 (25 kg Compost + 50% K through Polyhalite + 50% P through PROM) recording the highest determinate inflorescences (93.34) and indeterminate inflorescences (407.56), on par only with T_8, while the control exhibited the minimum values reflecting poor floral differentiation under nutrient deficiency; similarly, flowers per inflorescence peaked at 195.34 in T_9 (25 kg Compost + 50% K through Polyhalite + 50% P through PROM), comparable solely to T_8 (194.10), versus the lowest in the control (160.52). The increased formation of indeterminate inflorescences may be partly explained by the known role of magnesium (Mg), which is a major constituent of chlorophyll and increases the efficiency of photosynthesis and source capacity. Sufficient Mg levels increase carbon fixation, sucrose biosynthesis and phloem loading, thereby maintaining a steady flow of assimilates to the reproductive meristems and extended meristem activity [21,22]. Moreover, potassium (K) increases photoassimilate transport and reproductive sink activity, while sulphur (S) is involved in protein biosynthesis. The results could reflect enhanced enzyme activity and meristem formation, thus maintaining floral growth. Calcium (Ca) also plays a role in maintaining cell wall and membrane integrity in differentiating floral tissues, thus improving peduncle and floral organ strength [23]. At the same time, phosphorus nutrition from PROM and compost application promotes nucleic acid synthesis and cell division during inflorescence initiation, thus maintaining overall floral growth and development [24].

Inflorescence length and width

Inflorescence size parameters of avocado cv. TKD-1 (Table 2) improved markedly under integrated nutrient treatments, with T_9 (25 kg Compost + 50% K through Polyhalite + 50% P through PROM) recording the maximum length (8.45 cm) and width (13.45 cm), statistically on par only with T_8 (50% RDF + 50% K through Polyhalite + 50% P through PROM), while the control exhibited the smallest dimensions due to restricted assimilate supply under nutrient deficiency. Potassium in polyhalite promotes sugar biosynthesis and transport, thereby providing sufficient energy for flower differentiation, while sulphur functions in RuBisCO and protein biosynthesis, leading to better assimilate partitioning to flowers [1,15]. Magnesium further promotes chlorophyll and photosynthesis efficiency and in combination with potassium, calcium and sulphur, it promotes peduncle development and vigorous flowering [25,26]. These actions are further amplified by PROM and compost, which improve nutrient availability and recycling, thereby promoting growth and flowering responses as previously observed in Narcissus tazetta using integrated organic-mineral fertilization [21,27,28].

Flower drop

Flower drop percentage varied significantly across treatments, with the lowest recorded in T_9 (90.49%) statistically comparable only with T_8 (90.64%), while the untreated control exhibited the highest (94.67%), reflecting poor floral retention under nutrient-deficient conditions. The decrease in floral drop due to integrated organic-mineral nutrition is explained by enhanced structural and physiological stability of floral parts. Calcium in polyhalite enhances cell wall resistance in the abscission zone, preventing early drop, while potassium's role in osmotic regulation and stress protection alleviates abiotic stress-induced abscission [25,29,30]. Moreover, organic amendments have been reported to decrease fruit drop and increase retention by promoting phenological stability [31]. The integrated use of polyhalite, PROM and compost, therefore, maintains assimilate, hormone and cell integrity, thus reducing drop in nutrient-deficient control treatments [32].

Fruit-bearing efficiency characteristics

The parameters of fruit set and fruit-bearing efficiency were significantly affected by the nutrient treatment levels applied (Table 3). The minimum days taken from flowering to fruit set were recorded in T_9 (12.56 days), which was at par only with T_8 (13.13 days) and significantly better than all other treatments. The control took the longest time (28.45 days), which was significantly delayed. The fruit set percentage was significantly affected by integrated nutrient management. T_9 (25 kg Compost + 50% K through Polyhalite + 50% P through PROM) recorded the highest fruit set (9.51%), which was statistically at par only with T_8 (9.36%), while the control recorded the lowest fruit set (5.33%). The duration from fruit set to harvest was significantly reduced by the combined application of compost, polyhalite and PROM. T_9 recorded the shortest fruit development period (110.67 days), which was statistically at par only with T_8 (111.13 days), while the control took the longest time (123.67 days). The fruit drop percentages were significantly lower in the integrated nutrient management treatments than RDF and control (Table 3).

Table 3
Organic mineral nutrients on fruit-bearing efficiency characteristics of avocado cv. TKD 1

Treatment Details	Days from flowering to fruit set	Fruit set (%)	Days from fruit set to harvest	Early fruit drop (%)	Summer fruit drop (%)	Fruit retention (%)	Yield (kg tree^{-1})
T_1	24.91^{e}	6.26^{e}	120.77^{e}	69.33^{e}	47.77^{e}	16.24^{e}	163.48^{e}
T_2	22.12^{d}	6.99^{d}	118.49^{d}	67.22^{d}	46.01^{d}	17.59^{d}	206.23^{d}
T_3	18.76^{c}	7.88^{c}	115.74^{c}	64.68^{c}	43.90^{c}	20.11^{c}	257.66^{c}
T_4	21.62^{d}	7.12^{d}	118.08^{d}	66.84^{d}	45.70^{d}	18.31^{d}	213.87^{d}
T_5	15.62^{b}	8.70^{b}	113.18^{b}	62.31^{b}	41.92^{b}	22.08^{b}	305.62^{b}
T_6	16.15^{b}	8.56^{b}	113.60^{b}	62.71^{b}	42.25^{b}	21.75^{b}	297.63^{b}
T_7	19.01^{c}	7.81^{c}	115.94^{c}	64.87^{c}	44.05^{c}	19.95^{c}	253.84^{c}
T_8	13.13^{a}	9.36^{a}	111.13^{a}	60.43^{a}	40.35^{a}	23.65^{a}	343.85^{a}
T_9	12.56^{a}	9.51^{a}	110.67^{a}	59.98^{a}	40.02^{a}	24.00^{a}	352.54^{a}
T_{10}	28.45^{f}	5.33^{f}	123.67^{f}	72.01^{f}	49.99^{f}	14.02^{f}	109.26^{f}
S.Ed.	1.06	0.27	0.87	0.80	0.667	0.84	0.67
C.D. @ 5%	2.22	0.58	1.82	1.68	1.400	1.75	1.40

T_1- 100% RDF, T2–50% RDF + 25 kg compost, T_3 – 50% RDF + 50% K through Polyhalite, T_4 – 50% RDF + 50% P through PROM, T_5 – 50% K through Polyhalite + 50% P through PROM, T_6 – 25 kg compost + 50% K through Polyhalite, T_7 – 25 kg compost + 50% P through PROM, T_8 – 50% RDF + 50% K through Polyhalite + 50% P through PROM, T_9 – 25 kg compost + 50% K through Polyhalite + 50% P through PROM, T_{10} - Control. Treatments with the same letter grouping are not significantly different.

T_9 (25 kg Compost + 50% K through Polyhalite + 50% P through PROM) had the lowest early fruit drop (59.98%) and summer fruit drop (40.02%), being statistically at par only with T_8 (50% RDF + 50% K through Polyhalite + 50% P through PROM), while the highest fruit drop was observed in the control. Consequently, the maximum fruit retention was observed in T_9 (24.00%), which was statistically at par only with T_8 (23.65%), while the lowest fruit retention was observed in the control (14.02%). The maximum yield of avocado cv. TKD-1 was obtained in T_9 (25 kg compost + 50% K through polyhalite + 50% P through PROM), which produced 352.54 kg tree^{-1} and was statistically at par only with T_8 (50% RDF + 50% K through polyhalite + 50% P through PROM), which produced 343.85 kg tree^{-1}, while the control (T_{10}) produced the lowest yield of 109.26 kg tree^{-1}, indicating poor reproductive efficiency.

The shorter interval from flowering to fruit set observed under integrated nutrient management may be associated with improved reproductive processes and nutrient availability. This response could be partly explained by the known roles of potassium in reproductive development and phosphorus in energy transfer and cell division [14,21,33]. Phosphorus from PROM supporting ATP-dependent fertilization and embryo division and magnesium-stimulated photosynthesis to ensure uninterrupted assimilate supply. Increased fruit set is due to enhanced flowering quality, increased carbohydrate transport and proper hormonal regulation because of potassium-regulated IAA oxidase [34], phosphorus-stimulated cell division and sulphur-induced protein synthesis. Comparable increases in fruit set and reduced drop due to organic-mineral fertilizer have been observed in citrus and pomegranate [35,36]. The shorter fruit set-to-harvest interval indicates faster metabolic efficiency

due to potassium-regulated sugar accumulation, magnesium-stimulated photosynthesis and phosphorus-stimulated energy metabolism, unlike nutrient-deficient controls. The reduced early and summer fruit drop and increased fruit retention associated with improved nutrient availability and nutrient-use efficiency. Possible mechanisms include enhanced carbohydrate transport, improved reproductive development and greater stress tolerance, which together contribute to reduced abscission and better fruit retention [30,32].

In general, a balanced polyhalite-PROM-compost nutrient regime promotes the energy-demanding flowering and fruiting phases, leading to improved reproductive performance and lower abscission rates [22,37]. Phosphorus plays an important role in ATP-mediated energy transfer and several metabolic processes related to plant growth [1]. The improved fruit set observed in the present study may be associated with adequate phosphorus availability. Previous studies suggest that phosphorus may influence endogenous gibberellin activity, thereby supporting cell division, cell elongation, flowering and fruit development. Therefore, the response observed with polyhalite application is consistent with these reported physiological effects, although these mechanisms were not directly evaluated in the present study. The supply of phosphorus through PROM also improves nutrient availability and metabolic efficiency, which stimulate gibberellin-mediated growth responses in avocado. A balanced supply of potassium and sulphur improves flowering performance and the initiation of early fruits, hence increasing avocado productivity. Potassium helps in maintaining osmotic equilibrium, turgor and assimilate transport, hence contributing to fruit set and subsequent cell growth, while sulfur stimulates enzymatic activity and protein synthesis, which are critical for reproductive development. The joint application of K, S, Ca and Mg from polyhalite increases flower retention, fruit growth and ultimately fruit production, as reported in onion and other fruiting crops [38–41].

Conclusion

The integrated organic-mineral nutrient management practice showed a substantial improvement in flowering efficiency and fruiting performance of avocado cv. TKD-1 under high-density planting. The combined use of compost @ 25 kg tree^{-1} along with potassium from polyhalite (1.4 kg tree^{-1}) and phosphorus from PROM (0.52 kg tree^{-1}) resulted in enhanced flowering, inflorescence development, flower and fruit retention and fruit set and retention compared to RDF and the control. These results indicate that the integrated use of organic and mineral nutrient sources improved flowering, fruit retention and yield in avocado. The balanced supply of nutrients through compost, polyhalite and PROM may help enhance reproductive performance and productivity. The findings are based on a single location and one cropping season and require validation across multiple locations and seasons.

Declarations

Authors contribution

Sharvesh S: Investigation, data collection, data curation, formal analysis and original draft preparation.

Sathappan CT and Dhanasekaran D: Conceptualization, methodology development, supervision, critical review and editing of the manuscript.

Rameshkumar S and Vigneswari G: Resources, validation, review and editing.

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Ethics, Consent to Participate, and Consent to Publish declarations

The plant material used in this study consisted of cultivated avocado (*Persea americana* Mill.) cv. TKD-1 trees maintained at Pandrimalai, Dindigul district, Tamil Nadu, India. The study was conducted in accordance with applicable local and national guidelines for the use of plant material. The study did not involve the collection of wild plants. Permission for conducting the field experiment was obtained from the relevant orchard owner or authority, as applicable.

Clinical Trial Registration

Not applicable. This study was a field experiment conducted on avocado plants and did not involve human participants, animals or a clinical trial.

Competing Interests

The authors declare that they have no competing interests.

Data Availability

All the datasets generated and/or analysed during the present study are presented in the main manuscript.

Declaration

The authors declare that they have no competing interests**.**

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