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Research Paper

Susceptibility of vapour heat-treated "B74" mango fruit to internal disorders and mineral nutrient composition

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ABSTRACT

Supply of premium quality fruit to export markets is important for consumer satisfaction and repeat purchase. For 'B74' mango fruit, vapour heat treatment (VHT) is an export protocol for fruit fly control for market access. However, VHT has been associated with internal physiological disorders in 'B74' fruit. Susceptibility of 'B74' to internal disorders in association with VHT and flesh mineral composition was investigated. Fruit were sourced from orchards across three climatic regions of Australia: Northern Territory (NT), Far-north Queensland (FNQ), and South-east Queensland (SEQ). They were assessed over two successive seasons for internal disorders associations with mesocarp mineral composition. Flesh browning (FB) and flesh cavity with white patches (FCWP) defects were observed. FCWP was present only in VHT fruit. FB was independent of VHT. Over the two seasons, the highest FB incidence was observed in NT fruit (20 %) and the highest FCWP in FNQ fruit (65 %). FB was not observed in fruit from SEQ in either season. Flesh [Ca] and [Mg] were highest in NT fruit. [N,B], N/Ca, K/Ca, and (K+Mg)/Ca were higher ($p \leq 0.05$) in fruit from SEQ. Significant ($p \leq 0.05$) positive correlations between FCWP and N/Ca, K/Ca, and (K+Mg)/Ca ratios and a negative correlation between FB and [B] were discerned by linear correlation and principal component analysis. However, strength of correlation and statistical significance levels varied over regions and seasons. This inconsistency suggests that other deterministic factors also influence VHT-induced internal disorders in 'B74' mango. 'Big data' sets encompassing preharvest factors along with 'at harvest' flesh mineral concentrations would potentially better inform predictive modelling of internal disorders expression in 'B74' fruit.

1. Introduction

Mangoes are a climacteric fruit susceptible to external and internal disorders. These include flesh cavity, internal browning, jelly seed, lenticel spots, soft nose, and under-skin browning (Kulkarni, 1992; Mishra et al., 2016; San et al., 2014, 2019; Wainwright and Burbage, 1989). Physiological defects negatively affect fruit texture, visual appeal, marketability, and consumer satisfaction (Oldoni et al., 2022). Susceptibility of mango fruit to physiological disorders depends on a variety of factors that include cultivar (viz., genetic), seasonal changes (viz., environmental), mineral nutrition, and postharvest practices (viz., management) (Hofman et al., 2012; Schaffer, 1994). Defects are problematic for the mango industry and afflict most cultivars (Krishna et al., 2020; Mogollón et al., 2020; Ullah et al., 2024b).

Pre- and postharvest factors have been investigated to determine cause and effect with respect to fruit predisposition to internal disorders (Léchaudel and Joas, 2007; Ullah, 2023; Ullah et al., 2024a). Prior research has linked mineral nutrient deficits with development of internal disorders, e.g., Ca (Bitange et al., 2020; Ma et al., 2018; Singh et al., 2013).

Ca plays critical roles in fruit development, cell wall strengthening, and signal transduction pathways (Hocking et al., 2016). Ca deficiency during early fruit development can lead to physiological disorders, including bitter pit in apple (Kalcsits et al., 2019), blossom end rot in

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Fig. 1. Growing regions and location of the VHT facility where the 'B74' mango fruit were harvested and treated, respectively. NT: Northern Territory, FNQ: Far-North Queensland, SEQ: Southeast Queensland, and VHT: Vapour heat treatment.

tomato (Ho et al., 1993), and internal breakdown and rots in avocado (Hofman et al., 2002; Ullah and Joyce, 2024). Ca deficiency in mango fruit has been associated with jelly seed (Raymond et al., 1998b), stem-end cavity (Raymond et al., 1998a), and spongy tissue (Ma et al., 2023).

As individual mineral nutrients like Ca have a role in fruit development and resilience, mineral nutrient balances (e.g., N/Ca, K/Ca) may be useful indices for robustness and quality (Bally, 2006; Ma et al., 2018; Torres and Saúco, 2004; Ullah et al., 2022). Robustness at harvest reflects the innate ability of fruit to withstand harvest and postharvest stresses, including phytosanitary treatments required for international trade. In long export supply chains, disinfestation may predispose fruit to physiological disorders and dimmish quality to consumers (Jacobi and Giles, 1997).

Around 68,600 tonnes of mango, worth approximately $Aus 217.9 million, are produced annually in Australia (Hort. Innovation Australia, 2023). The major cultivars are 'R2E2', 'Honey Gold', 'Kensington Pride', and 'B74' ('Calypso®'). About 7 % of total Australian production (4747 tonnes) was exported in 2022 (Hort. Innovation Australia, 2023). In the 2019/2020 mango season, 'B74' accounted for 25 % of total production from September to February (Hort. Innovation Australia, 2021). At eating ripe, 'B74' has characteristic bright yellow skin with red blush, good texture and flavour, a small seed, and fibre-free flesh (Hofman et al., 2010b).

For export to certain Asian markets (e.g., China, Korea), 'B74' mango fruit need to undergo vapour heat treatment (VHT) for fruit fly disinfestation (Jacobi and Giles, 1997; Singh and Saini, 2014). Fruit core temperature is raised to and maintained at 47 °C for 15 min using forced moisture-saturated air and then cooled to storage temperature (e.g., 18 °C) (Jacobi et al., 2001). For fruit that are not sufficiently robust at harvest, VHT may adversely affect fruit physiochemistry and elicit internal disorders (Mitcham and McDonald, 1993).

While demand for mangoes in international markets is strong, compromised internal quality poses a threat. The present study investigated the prevalence of internal disorders in export quality 'B74' fruit and the putative role of fruit minerals in susceptibility to VHT-induced internal disorders for 'B74' fruit from three production regions over two successive growing seasons.

2. Materials and methods

2.1. Description of experimental sites

'B74' mango fruit were sourced from three growing regions (Northern Territory (NT), Far-North Queensland (FNQ), and Southeast Queensland (SEQ)) over two successive fruiting seasons (2020 and 2021) (Fig. 1). The annual NT crop production cycle typically starts with flowering in late winter/early spring, and harvest commences in late September/October, depending upon temperature fluctuations (AMIA, 2022b). The annual crop production cycles for FNQ and SEQ start from July to late-August, with harvests beginning in late November and late January/early February, respectively (AMIA, 2022a). NT fruit were sourced mainly from farms near Katherine (14.479°S, 132.266°E) and Mataranka (14.925°S, 133.066°E), FNQ fruit from near Dimbulah (17.158°S, 145.099°E), and SEQ fruit from near Childers (25.136°S, 152.372°E). The orchards were of 10 –16-year-old trees on 'Kensington Pride' rootstock maintained under standard commercial practice (Hofman and Whiley, 2010; Hofman et al., 2010b; Whiley et al., 2006). Average monthly maximum and minimum air temperatures and rainfall data from the Australian Bureau of Meteorology website were obtained for the closest weather stations at Katherine (station number: 14,932, 14.52°S, 132.38°E), Dimbulah (station number: 31,051, 17.34°S, 144.93°E), and Childers South (station number: 39,303, 25.26°S, 152.28°E). Soil mineral analysis data was collected in each production region by the growers in routine nutrient management programs for analysis by NATA accredited commercial soil analysis laboratories.

2.2. Fruit sampling

Fruit were commercially harvested, de-sapped, and treated with fungicide (Sportak®: 55 ml/100L H_2O –30 s dip) as per commercial practice. They were then transported in refrigerated trucks (~16 °C) to

Table 1
Numbers of fruit assessed from each region over two seasons.

Region	Blocks	Total fruit assessed	Number of individually assessed fruit			
			Season 2020 +VHT	Season 2021 -VHT	+VHT	-VHT
NT	3	1602	246	242	576	538
FNQ	2	1652	216	150	648	638
SEQ	1	990	225	225	270	270

NT: Northern Territory, FNQ: Far-North Queensland, SEQ: Southeast Queensland, VHT: vapour heat treatment.

the VHT facility at Rocklea, Brisbane after harvest within 5 –6 days of harvest from NT (~3400 km) and 3 –4 days from FNQ (~1700 km). Fruit from SEQ were transported to the VHT facility within 1 –2 days (~350 km) of harvest in an airconditioned vehicle (~20 °C) (Fig. 1). Although SEQ fruit are not generally exported due to inconsistent quality across growing seasons (S. Grabbe, *pers. comm.*, 2020), they were included in this study as to if mineral nutrient imbalance is a contributing factor to inconsistent postharvest quality. Information on number of blocks and fruit samples assessed from regions is presented in Table 1. Fruit were sampled from the VHT facility multiple times throughout each season. At each event, they were assigned into six commercial packing trays containing 15 individual fruit with each tray representing a replicate. Three trays per sampling interval were subject to VHT, whereby fruit core temperature was raised to 47 °C and maintained for 15 min. Relative humidity was > 90 %. The remaining three trays were non-VHT fruit kept at room temperature (20 ± 2 °C) in the VHT facility. Fruit were cooled to 18 °C after VHT and transferred to the postharvest laboratory (~20 °C) at The University of Queensland, Gatton campus, about 100 km away. Postharvest and ripening assessments were duly conducted at 20 °C, without ethylene treatment.

2.3. Fruit assessments

The fruit ripening stage was determined subjectively using a hand firmness rating system (Hofman et al., 2010a): 0 = Hard (no 'give' in the fruit), 1 = Rubbery (slight 'give' in the fruit), 2 = Sprung (flesh deforms by 2 –3 mm with extreme thumb pressure), 3 = Firm soft (whole fruit deforms with moderate hand pressure), and 4 = Soft (whole fruit deforms with slight hand pressure). Incidence and severity of internal disorders were assessed by visual inspection at ripe (firmness stage 4) (Hofman et al., 2010a).

Fruit were then longitudinally sliced immediately adjacent to the seed. Incidence % was estimated as: (number of fruit with a disorder / total number of fruit) × 100. Severity for individual fruit was rated 0 –3: where, 0 = Healthy (no sign of disorder); 1= Slight (<25 % area of mesocarp affected); 2 = Moderate (25–50 % area of mesocarp affected); and 3 = Severe (> 50 % area of mesocarp affected).

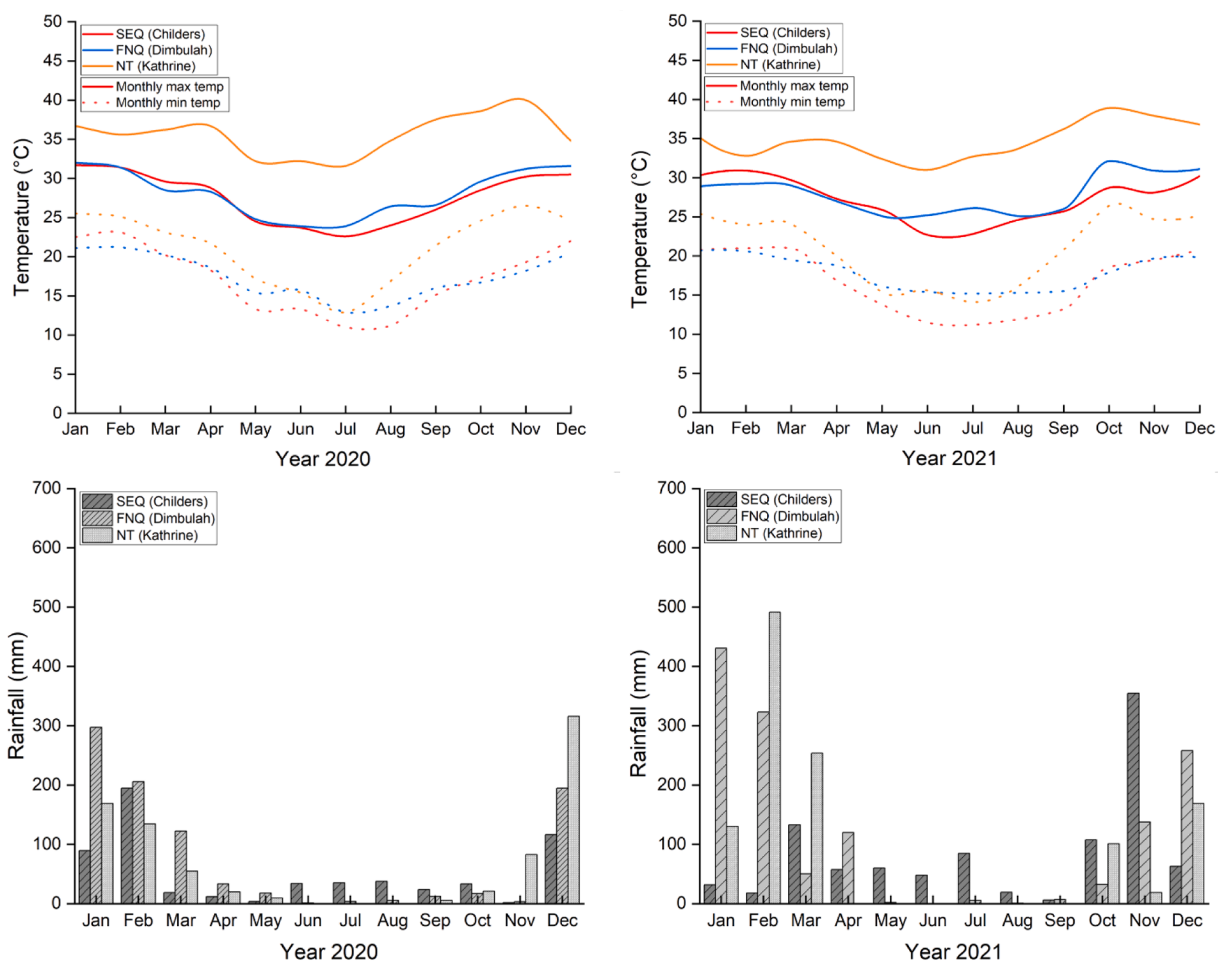

Fig. 2. Meteorological data from the three sites from which fruit were sourced for quality assessments and mesocarp mineral analyses in two consecutive seasons. The top two figures show maximum and minimum (solid and dotted lines, respectively) average monthly air temperatures for 2020 and 2021. The bottom two figures show the monthly average rainfall over two seasons for each of the selected sites. The fruit production cycles from flowering to harvest were April to September/October for NT, June/July to November/December for FNQ, and August/September to January/February for SEQ, respectively.

Table 2
Soil characteristics and mineral concentrations at 30 cm depth taken at the end of Jan 2021 and 2022 mango seasons for the three sampling regions. "-" denotes data not available.

Parameters	Unit	NT		FNQ		SEQ	
		2020	2021	2020	2021	2020	2021
pH (H_2O)	–	8.77	8.85	–	6.07	7.50	7.23
CEC	meq/100g	9.87	7.72	–	3.40	3.97	3.21
Ca	meq/100g	7.27	5.45	–	2.56	2.62	2.29
Mg	meq/100g	2.30	2.16	–	–	0.94	0.61
K	meq/100g	0.20	0.08	–	0.18	0.21	0.19
Na	meq/100g	0.10	0.01	–	–	0.16	0.07
Ca base saturation	% of CEC	73.87	70.64	–	75.60	66.01	69.94
Mg base saturation	% of CEC	24.67	28.24	–	–	23.88	19.58
K base saturation	% of CEC	2.00	1.10	–	5.24	5.41	6.11
Na base saturation	% of CEC	0.87	0.00	–	–	4.16	2.42
Ammonium - N	mg/kg	1.04	–	–	–	1	3.56
Nitrate - N	mg/kg	2.73	–	–	–	<1	< 1
B	mg/kg	0.30	0.40	–	0.27	0.48	0.58
P	mg/kg	54.00	57.59	–	–	43.67	53.83
S	mg/kg	5.67	5.53	–	–	9.67	8.41

NT: Northern Territory, FNQ: Far-North Queensland, SEQ; Southeast Queensland.

2.4. Fruit mineral analysis

For mineral analysis, two mesocarp sections (~2 × 2 × 2.6 cm) from the broadest point of the fruit cheek were obtained for five fruit per tray after VHT, and duly combined as a composite sample per tray. Additionally, mesocarp sections from individual healthy or disorder fruit were separated, dried at 65 °C in a fan-forced oven for 3 days, and ground to fine powder using a laboratory scale mini ball mill (Retsch Mixer Mill MM 400). Total N was measured using LECO C/NS928 carbon/nitrogen combustion analyser at combustion temperature 1250 °C (Flanagan et al., 2022). Other minerals, including Ca, Mg, K, P, and B, were measured using inductively coupled plasma-optical emission spectrometry (ICPOES: Thermo iCAP PRO XP) (Altundag and Tuzen, 2011). Tissue samples were digested in an open vessel with a 5:1 mixture of nitric and perchloric acids heated to 200 °C. The forward power for the ICPOES plasma was 1200 W. Samples were aspirated into the spectrometer using a concentric nebuliser with a Tracey spray chamber. The instrument was operated in radial mode for macronutrients and axial mode for micronutrients. All results were expressed as mg/kg on a dry weight basis.

2.5. Statistical analysis

Incidence and severity data on internal disorders and mesocarp mineral concentrations were analysed by two-way analysis of variance (ANOVA). Fruiting season was factor A and region factor B, and means were compared at a 5 % confidence level by Tukey's HSD test (Ferreira et al., 2014). Data normality distribution was determined by the Shapiro-Wilk normality test (Razali and Wah, 2011). Pearson's correlation coefficients (r) were determined to relate mineral nutrients to internal disorders (Schober et al., 2018). Multivariate analysis was performed using principal component analysis (PCA) (Biermann et al., 2022). All statistical analyses were performed in R (4.0.2) and graphs were prepared using R-packages, viz., ggplot2 (Wickham, 2011) and gplots (Warnes et al., 2009).

3. Results

3.1. Weather and soil conditions

NT experienced higher air temperatures than the two other regions in both years, with average maximum air temperatures reaching 40 °C around harvest in summer (Fig. 2). Site-specific differences in soil properties were also evident between regional farm sites. The soil at the farm in the NT was mildly alkaline (pH 8.8) with high cation exchange capacity (CEC), Ca (meq/100g), and Mg (meq/100g) as compared to the SEQ farm site (Table 2). The cationic balance by base saturation of CEC for Ca % was lower at the SEQ site. On the other hand, K % was high at the SEQ and FNQ sites as compared to the NT farm site (Table 2). Na % was much higher in SEQ than NT soil.

3.2. Occurrence and severity of internal disorders

The two distinct internal disorders observed in export quality 'B74' mango were flesh cavity with white patches (FCWP) and flesh browning (FB) (Fig. 3). FCWP was characterised by dry-white honeycomb-like cavities in the inner mesocarp near the seed and was only present in fruit subject to VHT (Fig. 3b). The absence of off-odour distinguished FCWP from spongy tissue disorder (Oak et al., 2019).

FB was characterised by darkening and discolouration in the fruit mesocarp at eating ripe (Fig. 3c). It presented in both VHT and non-VHT fruit. Fig. 4 shows the regional distribution of % incidence and the severity of both FCWP and FB disorders in VHT-treated fruit over two seasons.

Incidences of both disorders varied significantly ($p \leq 0.05$) in fruit sourced from different production regions and seasons. The mean values

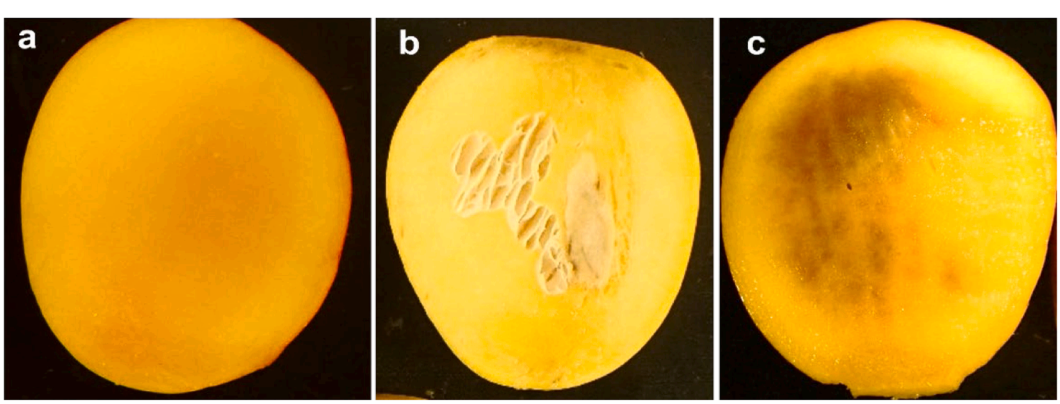

Fig. 3. Cross-section of ripe 'B74' mango fruit exhibiting internal disorders: a. Healthy (no disorder), b. Flesh Cavity with White Patches (FCWP), and c. Flesh Bowning (FB).

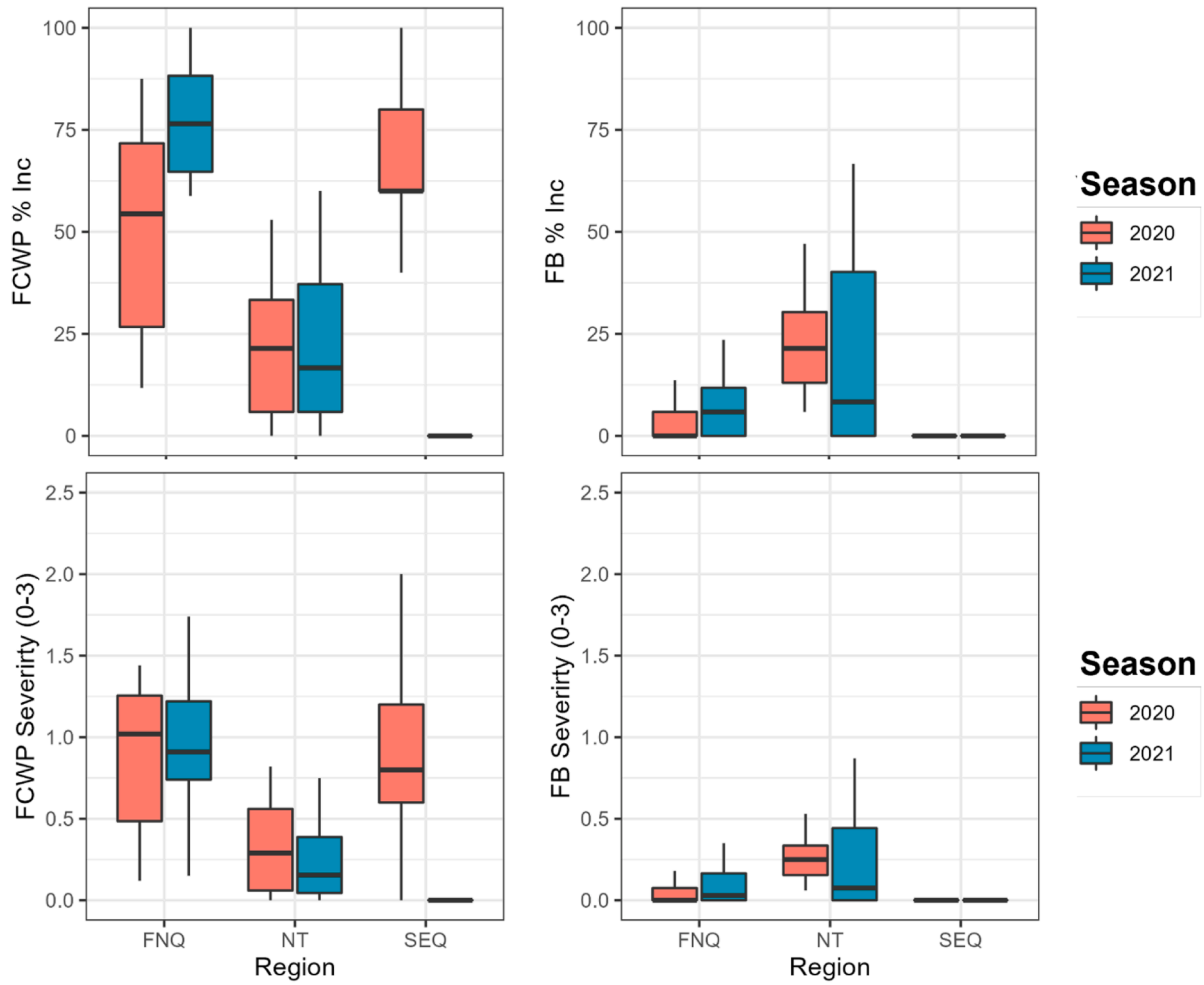

Fig. 4. Box and Whiskers plots of percent incidence (% Inc) and severity (0–3) of FCWP and FB disorders in 'B74' mango from three production regions over two seasons. Upper and lower whiskers represent 25 % and 25 % of the data. Coloured boxes represent the intermediate 50 % data and the transverse lines within the boxes is the median separating the value in two equal parts. NT: Northern Territory, FNQ: Far-North Queensland, SEQ; Southeast Queensland, FCWP: flesh cavity with white patches, FB: flesh browning.

Table 3
Incidence (%) and severity of internal disorders in 'B74' mango. Means followed by the same letter in each column are not significantly different at $p \leq 0.05$ according to Tukey's HSD test.

Internal disorders at eating ripe stage				
Season (S)	FCWP Incidence (%)	FCWP Severity	FB Incidence (%)	FB Severity
2020	52.41 [a]	0.79 [a]	5.35	0.06
2021	29.19 [b]	0.37 [b]	8.71	0.10
Significance	*<0.001*	*<0.001*	*0.06*	*0.73*
Region (R)				
NT	22.44 [c]	0.27 [c]	20.01 [a]	0.24 [a]
FNQ	64.98 [a]	0.99 [a]	8.23 [b]	0.08 [b]
SEQ	31.52 [b]	0.44 [b]	0.00 [c]	0.00 [c]
Significance	*<0.001*	*<0.001*	*<0.001*	*<0.001*
S × R				
2020 × NT	20.72 [bc]	0.34 [b]	23.17 [a]	0.26 [a]
2020 × FNQ	50.21 [a]	0.87 [a]	3.13 [bc]	0.05 [bc]
2020 × SEQ	63.56 [a]	0.91 [a]	0.00 [c]	0.00 [c]
2021 × NT	23.07 [b]	0.25 [b]	18.88 [a]	0.23 [a]
2021 × FNQ	69.53 [a]	0.96 [a]	9.80 [b]	0.10 [b]
2021 × SEQ	4.81 [c]	0.04 [b]	0.00 [c]	0.00 [c]
Significance	*<0.001*	*<0.001*	*0.01*	*0.01*

NT: Northern Territory, FNQ: Far-North Queensland, SEQ: Southeast Queensland, FCWP: flesh cavity with white patches, FB: flesh browning.

of FCWP incidence ranged from 4.8 % to 69.5 % (Table 3). Overall, FCWP incidence was significantly ($p \leq 0.001$) lower in 2021 (29.2 %) as compared to 2020 (52.4 %). NT fruit consistently showed a significantly ($p \leq 0.001$) lower incidence of FCWP (22.4 %) as compared to SEQ (31.5 %) and FNQ (64.9 %) at the ripe stage when two years data were pooled (Table 3). There was no significant ($p > 0.05$) difference in FCWP incidence in fruit from FNQ in 2020 (50.2 %) and 2021 (69.5 %) and with fruit from SEQ in 2020 (63.6 %). However, in 2021, SEQ fruit had a significantly ($p \leq 0.001$) lower incidence of FCWP disorder (4.8 %).

The incidence of FB was significantly ($p \leq 0.001$) higher in NT fruit (20.0 %), followed by those from FNQ (8.2 %) (Table 3). No incidence of FB was recorded in SEQ fruit in any season. The severity of FCWP and FB across all regions and seasons followed a similar trend to the incidence of these disorders. Overall, NT fruit had a significantly ($p \leq 0.001$) higher incidence of FB, and FNQ fruit had highest FCWP and moderate FB incidence and severity in both seasons.

3.3. Mesocarp mineral nutrient concentrations of 'B74' mango

There were considerable variations in mesocarp mineral concentrations in 'B74' mangoes across regions and seasons (Fig. 5). Fruit from SEQ had significantly ($p \leq 0.01$) higher [B], N/Ca, K/Ca, and (K+Mg)/Ca over the two fruiting seasons than did those from NT and FNQ (Table 4). However, Ca and Mg concentrations were significantly ($p \leq$

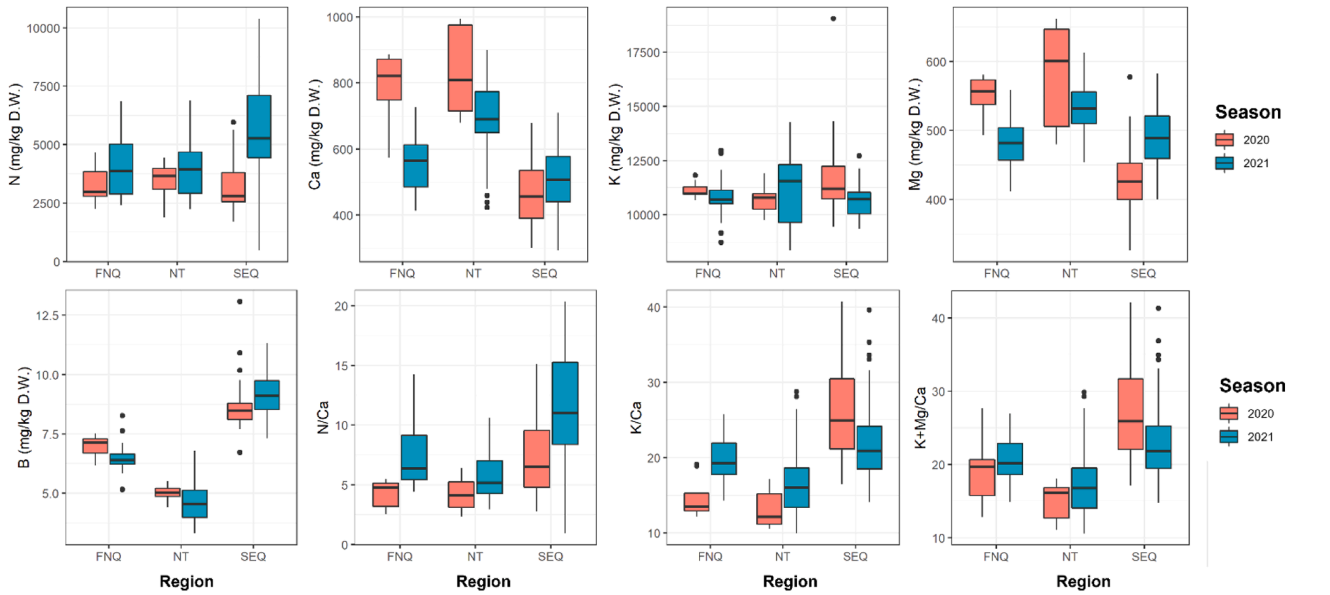

Fig. 5. Mineral nutrient concentrations in mesocarp of 'B74' mango sourced from different production regions over the two fruiting seasons. Upper and lower whiskers represent 25 % and 25 % data. The coloured boxes represent the intermediate 50 % data and transvers lines within the boxes are the median separating the value in two equal parts. NT: Northern Territory, FNQ: Far-North Queensland, SEQ: Southeast Queensland.

Table 4
Mineral nutrient concentrations across regions and seasons for 'B74' mango flesh. Means followed by the same letter in each column are not significantly different at $p \leq 0.05$ according to Tukey's HSD test.

Mesocarp mineral concentrations at harvest (mg/kg D.W.)								
Season (S)	N	Ca	K	Mg	B	N/Ca	K/Ca	(K±Mg)/Ca
2020	3287 ^{b}	593.9	11,350 ^{a}	480.5 ^{b}	7.62 ^{a}	6.26 ^{b}	21.4 ^{a}	23.06 ^{a}
2021	4627 ^{a}	579.7	10,852 ^{b}	502.2 ^{a}	6.96 ^{b}	8.46 ^{a}	19.69 ^{b}	20.59 ^{b}
Significance	*<0.001*	*0.34*	*0.004*	*0.002*	*<0.001*	*<0.001*	*0.01*	*<0.001*
Region (R)								
NT	3771 ^{b}	734.8 ^{a}	11,022	544.0 ^{a}	4.73 ^{c}	5.38 ^{b}	15.65 ^{c}	16.69 ^{c}
FNQ	3935 ^{ab}	607.9 ^{b}	10,921	498.8 ^{b}	6.54 ^{b}	6.80 ^{b}	18.63 ^{b}	20.28 ^{b}
SEQ	4502 ^{a}	486.2 ^{c}	11,080	463.3 ^{c}	8.94 ^{a}	9.48 ^{a}	23.81 ^{a}	24.79 ^{a}
Significance	*0.01*	*<0.001*	*0.967*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
S × R								
2020 × NT	3410 ^{b}	835.9 ^{a}	10,711 ^{ab}	578.7 ^{a}	5.02 ^{d}	4.20 ^{c}	13.12 ^{c}	14.88 ^{c}
2020 × FNQ	3228 ^{b}	779.5 ^{ab}	11,131 ^{ab}	548.6 ^{ab}	6.97 ^{c}	4.24 ^{c}	14.66 ^{c}	18.81 ^{bc}
2020 × SEQ	3261 ^{b}	463.7 ^{d}	11,621 ^{a}	429.6 ^{d}	8.66 ^{b}	7.48 ^{b}	25.96 ^{a}	26.92 ^{a}
2021 × NT	3900 ^{b}	698.7 ^{b}	11,133 ^{ab}	534.1 ^{b}	4.63 ^{d}	5.81 ^{bc}	16.55 ^{c}	17.34 ^{c}
2021 × FNQ	4153 ^{b}	555.1 ^{c}	10,857 ^{b}	483.5 ^{c}	6.40 ^{c}	7.59 ^{b}	19.86 ^{b}	20.74 ^{b}
2021 × SEQ	5535 ^{a}	504.9 ^{cd}	10,630 ^{b}	490.9 ^{c}	9.17 ^{a}	11.16 ^{a}	22.01 ^{b}	23.02 ^{b}
Significance	*0.004*	*<0.001*	*0.003*	*<0.001*	*<0.001*	*0.01*	*<0.001*	*<0.001*

NT: Northern Territory, FNQ: Far-North Queensland, SEQ: Southeast Queensland.

Table 5
Correlation coefficients (r) between 'B74' mango flesh mineral concentrations at harvest and incidence of internal disorders at ripe stage for each region and season. '*, **, ***' denote levels of significance of correlation at $p \leq 0.05$, 0.01 and 0.001, respectively.

Nutrients	FCWP Incidence (%)						FB Incidence (%)					
	NT		FNQ		SEQ		NT		FNQ		SEQ	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
N	0.59*	ns	0.67*	ns	0.42**	ns	ns	ns	0.63*	ns	–	–
Ca	ns	−0.33*	−0.55*	ns	ns	ns	ns	ns	ns	ns	–	–
K	0.52*	0.31*	ns	ns	0.32*	0.30*	ns	0.68***	0.46*	0.62***	–	–
Mg	0.87***	−0.34*	ns	ns	ns	ns	ns	ns	ns	ns	–	–
B	−0.59*	ns	ns	ns	ns	ns	ns	ns	ns	−0.44**	–	–
N/Ca	ns	0.37*	0.88***	ns	0.46**	ns	ns	0.37*	ns	ns	–	–
K/Ca	ns	0.48**	0.46*	0.32*	0.44**	ns	ns	0.52***	ns	ns	–	–
(K+Mg)/Ca	0.72**	0.47**	0.83***	0.32*	0.44**	ns	ns	0.51***	ns	ns	–	–

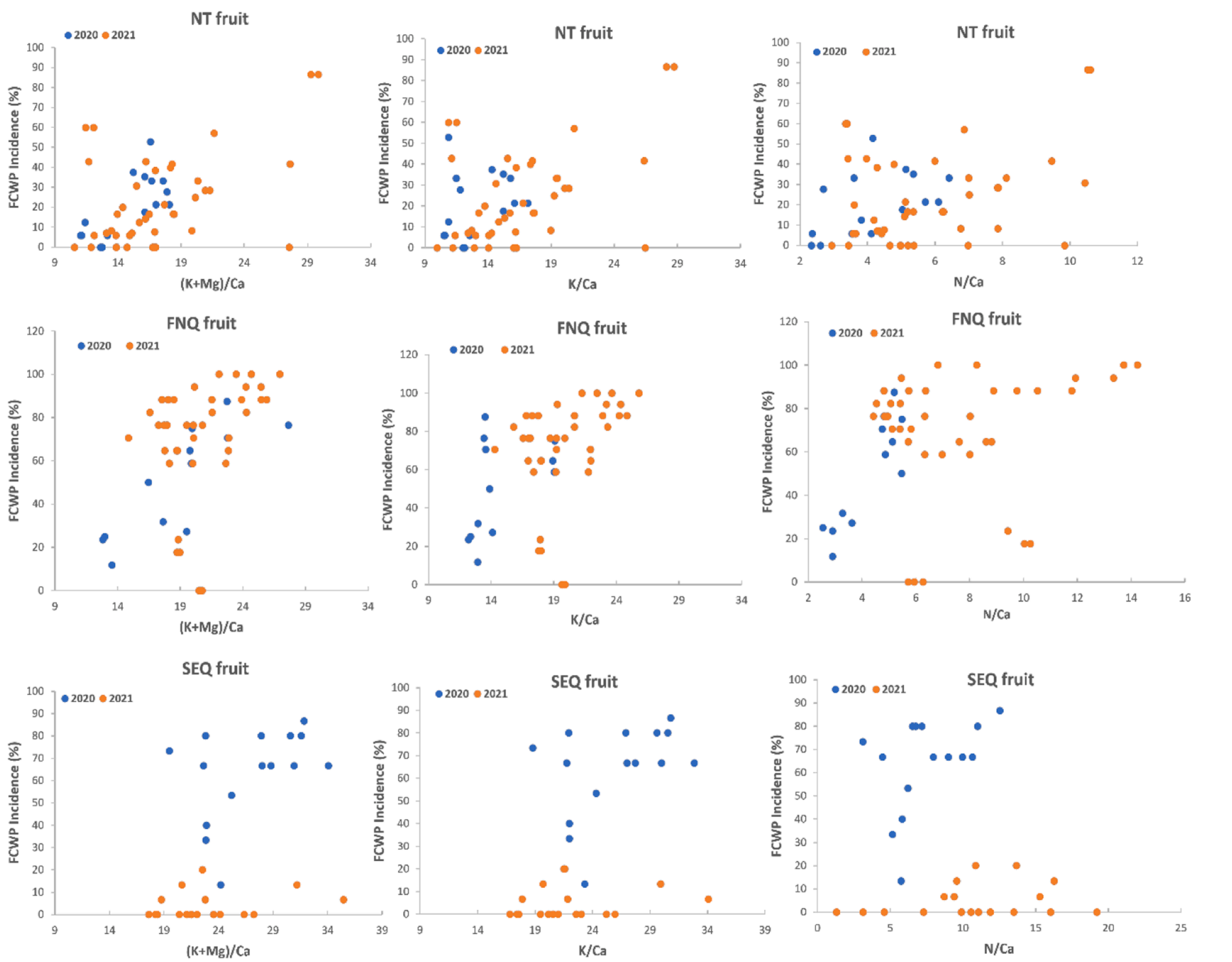

Fig. 6. Scatter plots of incidence of flesh cavity with white patches (FCWP) disorder versus mineral nutrient ratios in 'B74' mango flesh across three different production regions over two seasons. Each data point represents the % incidence of 15 sample fruit.

0.001) higher in NT fruit compared to those in FNQ and SEQ fruit. There was no significant ($p > 0.05$) difference in flesh K concentrations across the three regions and the two seasons (Table 4). Overall, seasonal influences on mineral concentrations across all regions were significant ($p \leq 0.01$), except for Ca. For region × season interaction, [Ca] was significantly ($p \leq 0.001$) higher in both NT and FNQ fruit in 2020 as compared to 2021. However, there was no significant interaction ($p > 0.05$) in Ca concentrations of SEQ fruit in both years. A similar trend of no significant interaction ($p > 0.05$) was observed in Mg concentrations for NT and FNQ, but not for SEQ fruit (Table 4, Fig. 5). On the other hand, [B] was consistently and significantly ($p \leq 0.001$) higher in SEQ for both seasons and for FNQ fruit in 2021. Overall, NT fruit had significantly ($p \leq 0.001$) lower concentrations of B, compared to FNQ and SEQ fruit (Fig. 5). K/Ca and (K+Mg)/Ca were significantly ($p \leq 0.001$) higher in SEQ fruit in 2020, and N/Ca was highest in 2021.

3.4. Correlation of mineral nutrients and internal disorders in 'B74' mango

Associations between individual mineral nutrient concentrations and internal disorders expression were inconsistent across regions and fruiting seasons (Table 5). On the other hand, their ratios, as N/Ca, K/Ca, and (K+Mg)/Ca, were relatively consistently correlated with internal disorders (Table 5).

FCWP incidence showed significant positive correlations with N concentrations in fruit from the NT ($r = 0.59$, $p < 0.05$), FNQ ($r = 0.67$, $p < 0.05$), and SEQ ($r = 0.42$, $p < 0.01$) in 2020. In contrast, no such correlations were evident in the 2021 fruiting season (Table 5). Individually [K] consistently showed a significant ($p \leq 0.05$) positive association with FCWP incidence in NT and SEQ fruit over two fruiting seasons, but not with FNQ fruit. [Ca] did not significantly ($p > 0.05$) correlate with FCWP incidence over the two fruiting seasons, except for fruit from NT ($r = -0.33$, $p < 0.05$) and FNQ ($r = -0.55$, $p < 0.05$) in 2021 and 2020, respectively (Table 5). [Mg] was not correlated with FCWP in FNQ and SEQ fruit in any season. Conversely for NT fruit, there was strong positive correlation ($r = 0.87$, $p < 0.001$) in the 2020 season and a negative correlation ($r = -0.34$, $p < 0.05$) in 2021. On the other hand, [B] only and negatively correlated with FCWP ($r = -0.59$, $p < 0.05$) in 2020 season for NT fruit. N/Ca, K/Ca, and (K+Mg)/Ca showed significant ($p \leq 0.05$) positive correlations with FCWP incidence in either first and/or second season across all regions.

Scatter plots clearly indicated the positive trend in FCWP incidence with N/Ca, K/Ca, and (K+Mg)/Ca ratios in NT and in FNQ fruit across both fruiting seasons (Fig. 6). For SEQ fruit, however, FCWP incidence increased with an increase in flesh K/Ca and (K+Mg)/Ca ratio, but not with N/Ca (Fig. 6). Strong correlations were observed for N/Ca in FNQ-2020 ($r = 0.88$, $p < 0.001$), for (K+Mg)/Ca in NT ($r = 0.72$, $p < 0.01$), and FNQ ($r = 0.83$, $p < 0.001$) in 2020 season. SEQ showed moderate correlation with mineral nutrient ratios in 2020 and no significant ($p > 0.05$) correlation with any of the mineral nutrient ratio in 2021

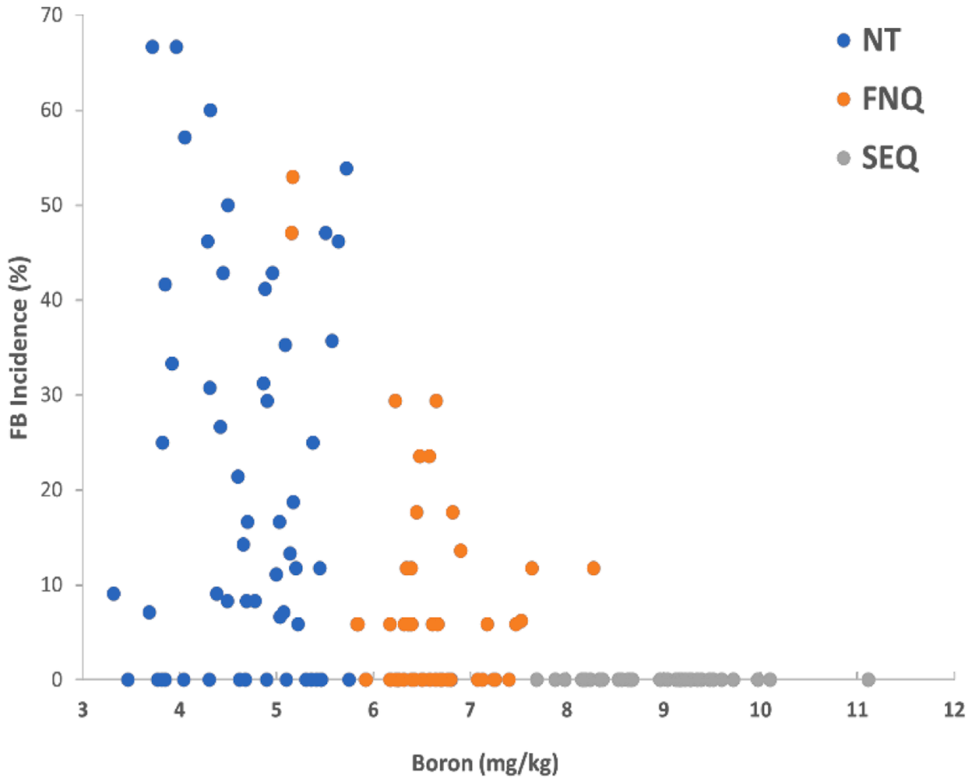

Fig. 7. Scatter plot of flesh browning (FB) disorder versus [B] in 'B74' mango flesh across three different production regions over two seasons. Each data point represents an average of 15 sample fruit.

Table 6
Mineral concentrations in the mesocarp of healthy and FCWP disordered 'B74' mango fruit from different production regions ($n = 3$). Means followed by the same letter in each column are not significantly different at $p \leq 0.05$ according to the Tukey's HSD test.

Region	FCWP Severity	Mesocarp mineral concentrations (mg/kg D.W.)						
		N	Ca	K	Mg	N/Ca	K/Ca	(K+Mg)/Ca
SEQ	Healthy	3690.9	527.52 [a]	11,691.9 [b]	460.54 [a]	7.04 [c]	22.29 [c]	23.17 [c]
	Slight	4084.3	487.77 [a]	12,891.8 [a]	440.74 [b]	8.38 [b]	26.44 [b]	27.34 [b]
	Moderate	3983.7	485.82 [a]	12,490.8 [a]	445.18 [b]	8.20 [b]	25.71 [b]	26.63 [b]
	Severe	3695.5	389.51 [b]	11,440.6 [b]	402.65 [c]	9.49 [a]	29.37 [a]	30.41 [a]
	Significance	*ns*	**	***	***	**	***	***
FNQ	Healthy	3812.6 [b]	630.21	11,230.9 [b]	503.55 [ab]	6.06 [b]	17.88	18.68 [b]
	Slight	4004.8 [ab]	568.37	12,308.3 [a]	534.96 [a]	7.17 [ab]	21.94	22.89 [a]
	Moderate	4278.6 [ab]	565.07	11,776.7 [ab]	488.08 [ab]	7.58 [a]	20.83	21.70 [ab]
	Severe	4627.6 [a]	580.45	12,037.7 [ab]	480.66 [b]	7.98 [a]	20.75	21.58 [ab]
	Significance	*	*ns*	*	*	*	*ns*	*
NT	Healthy	3460.7	791.97 [a]	9167.3	535.44	4.38 [b]	11.72 [b]	12.41 [b]
	Slight	3953.2	528.97 [b]	9145.6	544.55	7.53 [a]	17.34 [a]	18.37 [a]
	Moderate	4331.9	575.59 [b]	9945.1	532.73	7.56 [a]	17.30 [a]	18.23 [a]
	Severe	3480.8	522.81 [b]	9331.3	561.23	6.69 [ab]	17.95 [a]	19.04 [a]
	Significance	*ns*	**	*ns*	*ns*	*	**	**

Here, NT: Northern Territory, FNQ: Far-North Queensland, SEQ: Southeast Queensland, FCWP: flesh cavity with white patches, * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; ns: not significant.

(Table 5).

Incidence of FB was positively correlated with [N] in only FNQ-2020 fruit ($r = 0.63, p < 0.05$), with [K] in NT-2021 ($r = 0.68, p < 0.001$), and FNQ in both seasons (2020: $r = 0.46$, $p < 0.05$, 2021: $r = 0.62$, $p < 0.001$). Like FCWP, a negative correlation of [B] with incidence of FB was evident in FNQ-2021 fruit only (Table 5). Mineral nutrient ratios were not as significantly ($p > 0.05$) involved in FB incidence as in FCWP disorder. However, in 2021, NT fruit showed significant positive correlation between FB incidence and N/Ca ($r = 0.37, p < 0.05$), K/Ca ($r = 0.52$, $p < 0.001$), and (K+Mg)/Ca ($r = 0.51$, $p < 0.001$). On the other hand, fruit from SEQ had no FB over the two serial fruiting seasons.

The distribution of FCWP and FB across three regions over the two seasons in relation to mineral nutrients was further assessed by PCA to dimmish biasness in multivariate dataset and offer objective evaluation by compressing data variability into several key principal components (Biermann et al., 2022). The pooled data were plotted and clustered based on production regions for the first two principal components explaining 63.8.% of the total variation for FCWP disorder and 64.4 % of the variation for FB disorder (Figs. 8 and 9). Vectors indicating % incidence of FCWP were located on the same axis as mineral nutrient ratios, consistent with the strong positive correlation and higher proportional contribution to this disorder. Data grouping indicated higher susceptibility of SEQ fruit to FCWP due to prospectively higher K/Ca and (K+Mg)/Ca ratios (Fig. 8). NT fruit appeared more susceptible to FB

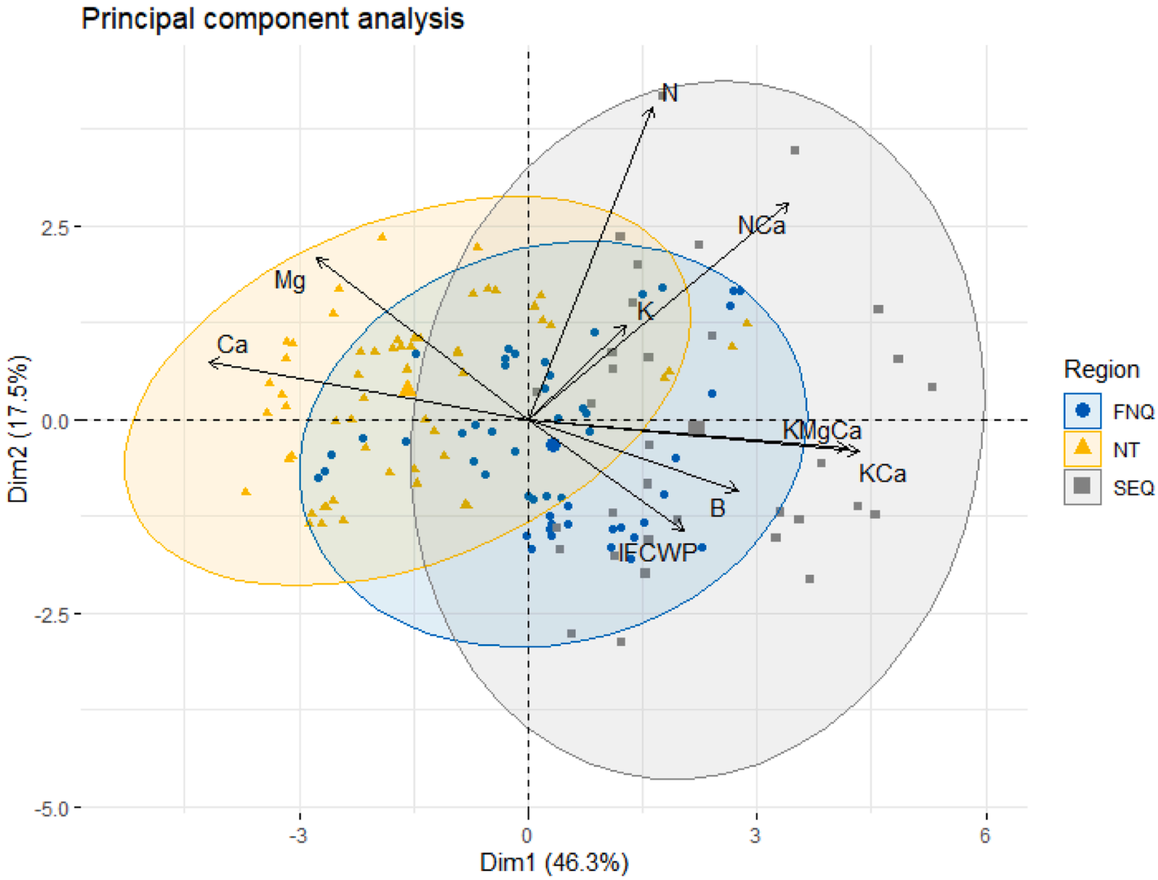

Fig. 8. Principal component analysis (PCA) of fruit nutrient concentrations and FCWP in 'B74' mango. Variance of component 1 (Dim1) = 46.3 % and that of component 2 (Dim2) = 17.5 %. Here, IFCWP = % incidence of FCWP, NCa = nitrogen to calcium ratio, KCa = potassium to calcium ratio, and KMgCa = potassium + magnesium to calcium ratio.

disorder, and data distribution from FNQ fruit showed equal susceptibility towards both disorders (Figs. 8 and 9). Furthermore, vectors pointing in opposite directions for [Ca] and [Mg] vs FCWP, and [B] vs FB suggest negative correlations of [Ca] and [Mg] and [B] with each disorder, respectively (Figs. 8 and 9). The negative relationship was apparent from the scatter plot of [B] against FB incidence from all three regions over two seasons (Fig. 7).

3.5. Mineral concentrations in healthy versus FCWP fruit

The flesh of individual healthy and FCWP disorder fruit with different severity levels was assessed for mineral analysis (Table 6). N concentrations were significantly ($p \leq 0.05$) higher in disordered fruit from FNQ as compared to healthy fruit. No significant ($p > 0.05$) differences in [N] were observed between healthy and FCWP fruit from SEQ and NT regions. [Ca] was significantly ($p \leq 0.01$) higher in healthy fruit across all regions except FNQ. A similar trend for [Ca] was observed for [Mg], except for NT where healthy fruit had lower [Mg] as compared to FCWP disordered fruit (Table 6). [P,Mn,Cu], and [B] were not significantly ($p > 0.05$) different between healthy and FCWP fruit from any production region. Mineral nutrient ratios, viz., N/Ca, K/Ca, and (K+Mg)/Ca, were significantly ($p \leq 0.05$) different between healthy and FCWP fruit across all regions except for K/Ca in FNQ. The highest values were noted in severely FCWP-affected, and the lowest in healthy fruit (Table 6).

4. Discussion

FCWP and FB were the most prominent defects observed and their prevalence varied significantly ($p \leq 0.05$) across both regions and seasons (Table 3).

Overall, fruit from FNQ and SEQ were more susceptible to FCWP compared to NT fruit. The disorders were evidently associated with lower [Ca,Mg], and higher [N] in the mesocarp over the two seasons, except for SEQ in the 2021 season (Tables 3 and 4). Involvement of Ca and Mg deficiencies in fruit predisposition to internal disorders has been reported for other mango cultivars (Assis et al., 2004; Burdon et al., 1991; Ma et al., 2018; Sharma and Singh, 2009). These associations were supported by mineral analysis of individual healthy and defective fruit, where healthy fruit had relatively higher [Ca] and [Mg], while FCWP fruit had relatively higher [N] and [K] (Table 6). High [Mg] and low [K] have previously been related to less internal defects and diseases in other fruit crops, notably avocado (Witney et al., 1990).

The relative deficiency or excess of one or more mineral nutrients can cause developmental abnormalities and metabolic disorders in fruit during postharvest storage and ripening (Andrade et al., 2022; Baugher et al., 2017; Donahue et al., 2021). For instance, low [Ca] and high K/Ca concentrations in apple peel have been associated with bitter pit disorder (Donahue et al., 2021; Kalcsits et al., 2019). Also, deficiency of [K, B], and [Zn] in citrus peel can associate with fruit cracking (Juan and Jiezhong, 2017).

Lower concentrations of Ca and Mg in FCWP fruit may relate to competition for uptake with K by the roots level, as well as relatively low mobility of these nutrients in the plant during the active fruit growth period (Hocking et al., 2016; Marschner, 1995; Tonetto de Freitas and Mitcham, 2012). Edaphic and environmental factors, including temperature and humidity during active fruit growth and development, are also likely modulators of Ca uptake and movement within the plant

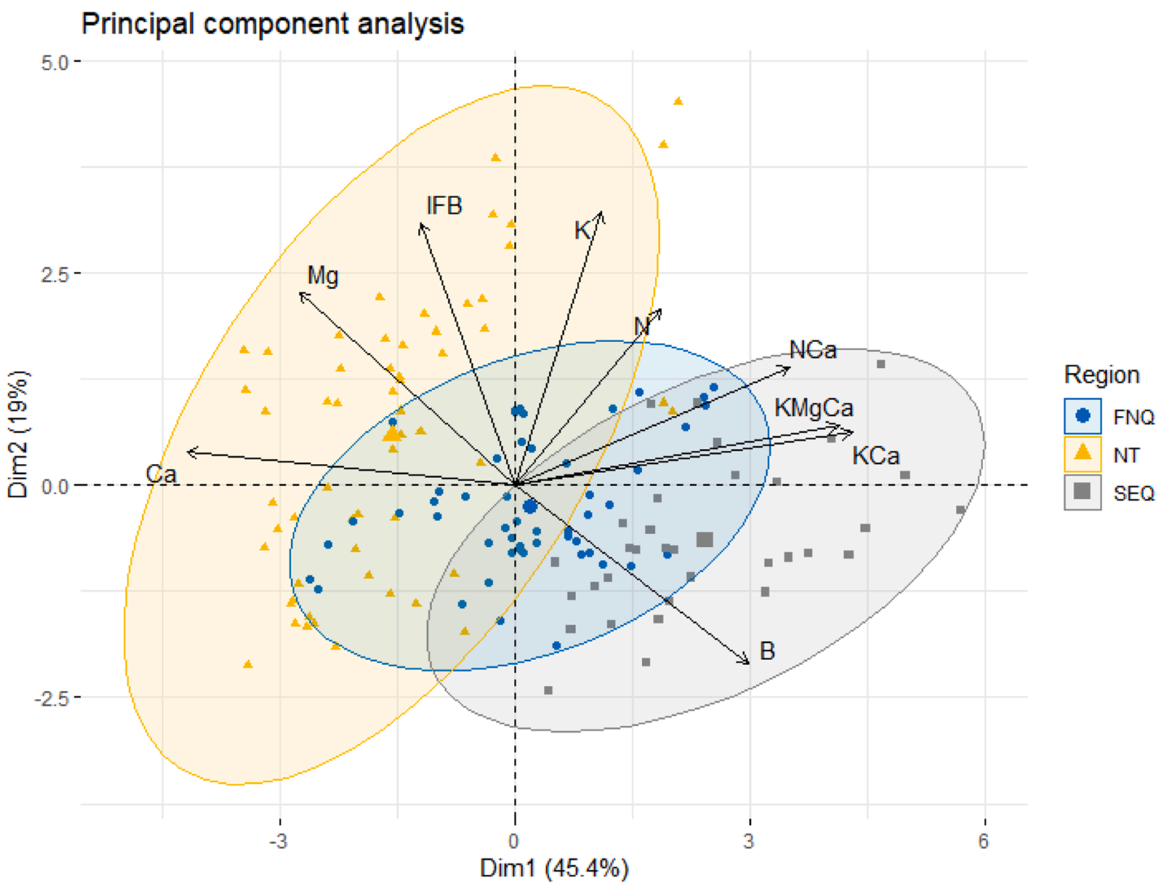

Fig. 9. Principal component analysis (PCA) of fruit nutrient concentrations and FB in 'B74' mango. Variance of component 1 (Dim1) = 45.4 % and that of component 2 (Dim2) = 19 %. Here, IFB = % incidence of FB, NCa = nitrogen to calcium ratio, KCa = potassium to calcium ratio, and KMgCa = potassium + magnesium to calcium ratio.

(Hewett, 2006; Léchaudel and Joas, 2007). NT soils had more available [Ca] with higher CEC and % base saturation in both seasons as compared to FNQ and SEQ soils (Table 2). The NT region also experienced higher average temperatures throughout the year compared to FNQ and SEQ (Fig. 2). As Ca predominantly moves through xylem under transpiration pull, relatively higher temperatures in NT may have increased VPD, which facilitated Ca uptake and distribution to NT fruit via high transpiration rates (Shivashankara and Mathai, 1999).

The mineral ratio of (K+Mg)/Ca showed consistently positive correlation ($p \leq 0.05$) with FCWP disorder across all seasons and regions (Table 5). Imbalance of [Ca,N,K], and [Mg] reportedly plays a vital role in fruit susceptibility to postharvest disorders and defects (Assis et al., 2004; Torres and Saúco, 2004). High N/Ca and K/Ca ratios are related to internal disorders of mango (Andrade et al., 2022; Assis et al., 2004; Ma et al., 2022). Assis et al. (2004) reported significantly ($p \leq 0.05$) higher N/Ca at 31:1 in 'Tommy Atkins' fruit flesh affected with a disorder as compared to non-defective fruit (17.1:1). Similarly, mineral nutrient ratios were significantly ($p \leq 0.05$) lower in healthy 'Keitt' mango flesh (N/Ca: ~7.5:1, K/Ca: 25:1) compared to fruit with spongy tissue (N/Ca: 30:1, K/Ca: ~95:1), jelly seed (N/Ca: 15:1, K/Ca: ~65:1), and flesh darkening (N/Ca: ~25:1, K/Ca: ~70:1) disorder (Andrade et al., 2022).

Principal component analysis supported positive correlation between mineral nutrient ratios and incidence of FCWP when all data across two seasons and three regions were pooled (Fig. 8). However, the range in ratios between healthy and disordered fruit differed across regions. For instance, the mean (K+Mg)/Ca ratio in fruit with severe disorders from NT was 19:1, which was higher than that for healthy fruit from SEQ (23.2:1) (Table 6). Such differences in absolute ratio values between healthy and disordered fruit indirectly suggest production region (viz., environment) as a contributor to variability in absolute numerical values of ratios alone as predictive indices. Another possible reason for NT fruit having lower incidence of FCWP could be long transit times between harvest and VHT (5 –7 days) as compared to FNQ (3 –4 days) and SEQ (1 –2 days) (viz., management). For instance, time before VHT may somehow 'condition' fruit; for example, upon starch hydrolysis into sugars and/or activation of heat shock proteins that help fruit to tolerate subsequent heat treatment (Brecht et al., 2020; Joyce and Shorter, 1994; Paull and Chen, 1990)

Data separation by PCA for region suggested that NT fruit were more susceptible to FB than FNQ and SEQ fruit (Fig. 9, Table 3). PCA also indicated a negative correlation between incidence and severity of FB with B concentration (Fig. 9). SEQ fruit had significantly ($p \leq 0.001$) higher [B] in both seasons, followed by FNQ and NT (Table 4). A role of [B] in maintaining internal fruit quality and/or susceptibility to internal breakdown in mango has been documented (Andrade et al., 2022; Ma et al., 2018; Saran and Kumar, 2011; Sharma and Singh, 2009). [B] in plant cells contributes to the network of pectic polysaccharides in the primary cell wall through borate-diester bonds (Bariya et al., 2014; Matoh, 1997), which is distinct from hemicellulose and cellulose components of the cell wall (Matoh, 1997). Formation of the pectin network provides cell wall stability, including in growth of reproductive cells, flower initiation, fruit retention, and in maintaining fruit internal quality (Bariya et al., 2014; Lovatt, 1990; Sharma and Singh, 2009; Smith et al., 1997b; Whiley et al., 1996). Improving [B] in fruit may thus improve tolerance to FB. For 'Dashehari' mango, Saran and Kumar (2011) reported reduced incidence of internal necrosis (browning) coincident with a significant ($p \leq 0.05$) increase in fruit [B] as a response to foliar application of 0.10 % disodium octaborate tetrahydrate. Foliar application of [B] has been reported to improve quality, yield, and shelf life for 'Dashehari' (Arvind et al., 2012) and 'Palmer' mango fruits (Oldoni et al., 2018). Combined foliar application of B and humic acid on 'Zebda' mango reportedly markedly reduced alternate bearing in concert with improved fruit size and total soluble solids (El-Hoseiny et al., 2020). Soil-applied B fertiliser increased pollen viability and fruit set and size in 'Hass' avocado (Smith et al., 1997a, 1997c).

In addition to mineral nutrients, other pre- and postharvest factors, such as crop load, maturity, and time-temperature unit integrals in the supply chain are other potential modulators of fruit predisposition to physiological disorders (East et al., 2009; Jacobi et al., 2001; Khanal et al., 2022, 2024; Rehman et al., 2015; Sivakumar et al., 2011). Notionally, promoting fruit robustness at harvest should mitigate adverse effects of postharvest rigours, like VHT, on fruit quality, and thereby diminish the incidence and severity of internal defects (Joyce et al., 2023; Joyce, 2021; Kiloes et al., 2023). Towards this end, the present study suggests that seasonal variations need to be characterised, including, but not limited to, the availability of soil minerals, crop load, and environmental conditions (Anderson et al., 2017; Bally, 2006; Hofman, 1995; Katrodia and Rane, 1981, 1988; Payne et al., 2014; Wang et al., 2018, 2019).

5. Conclusion

Incidence of internal disorders in 'B74' mango varied appreciably across production regions and fruiting seasons. Fruit from FNQ and SEQ were relatively more susceptible to express FCWP post-VHT. This predisposition was evidently associated with lower fruit flesh [Ca] and higher [N], K/Ca, and (K+Mg)/Ca ratios as compared to NT fruit. Flesh mineral involvement with FCWP was affirmed by assessing individual mineral concentrations of healthy (viz, normal) versus FCWP-affected fruit from all three regions. Notably, the (K+Mg)/Ca ratio could evidently be used as a predictive index for the likelihood of FCWP developing in the 'B74' fruit after VHT as it was consistently correlated across regions and seasons. In contrast, NT fruit were relatively prone to develop FB disorder, evidently in association with lower fruit flesh [B], suggesting that improving fruit [B] status could improve resistance to FB. Nonetheless and considering that correlations between mineral concentrations and prevalence of internal disorders were inconsistent over seasons, their expression is likely a multi-variate issue. Accordingly, it is imperative that more comprehensive studies capturing a broad range of preharvest factors in addition to mineral nutrition be undertaken. Ultimately, a 'big data' approach should enable reliable predictive modelling towards consistent supply of robust quality fruit for export markets, including those supply chains requiring stressful phytosanitary treatments, like VHT.

CRediT authorship contribution statement

Muhammad Asad Ullah: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amit Khanal:** Methodology, Investigation. **Priya Joyce:** Writing – review & editing, Supervision. **Neil White:** Writing – review & editing, Supervision. **Andrew Macnish:** Writing – review & editing, Supervision, Resources, Project administration. **Daryl Joyce:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Muhammad Asad Ullah reports financial support was provided by Cooperative Research Centre for Developing Northern Australia (CRC—NA). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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