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Roshni Bhagat
Research Scholer, College of
Agriculture & Research
Station, Raigarh,
Chhattisgarh, India

Shrikant L Sawargaonkar
Senior Scientist, ICAR-
Directorate of Medicinal and
Aromatic Plants Research,
Anand, Gujarat, India

Sandeep Kumar Painkra
Assistant Professor, College of
Agriculture & Research
Station, Raigarh,
Chhattisgarh, India

Nitin Kumar Rastogi
Principal Scientist, Directorate
of Farm, Indira Gandhi Krishi
Vishwavidyalaya, Raipur,
Chhattisgarh, India

Ganga Ram Rathiya
Associate Professor, College of
Agriculture & Research
Station, Raigarh,
Chhattisgarh, India

Corresponding Author:
Roshni Bhagat
Research Scholer, College of
Agriculture & Research
Station, Raigarh,
Chhattisgarh, India

Evaluation of indigenous germplasm of turmeric (*Curcuma longa* L.) for quality attributes

Roshni Bhagat, Shrikant L Sawargaonkar, Sandeep Kumar Painkra, Nitin Kumar Rastogi and Ganga Ram Rathiya

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Abstract

Turmeric (*Curcuma longa* L.) is one of the most economically important spice and medicinal crops of India, and its commercial value is governed principally by the curcumin, essential oil and oleoresin contents of the cured rhizome. Fifty-four indigenous accessions of turmeric, together with the national and local checks Roma, Suranjana, BSR-2, Chhattisgarh Haldi-1 (IT-2), Chhattisgarh Haldi-2 (IT-10) and CG Raigarh Haldi-3 (IT-36), were evaluated in a Randomized Complete Block Design with three replications during *Kharif* 2021-2022 and 2022-2023 at the Research Farm of the AICRP on Spices, CARS, Raigarh (Chhattisgarh), India. Rhizomes of the ten most promising accessions and the two principal checks were analysed for curcumin, essential oil and oleoresin contents. Substantial genotypic variability was recorded for all three quality traits. Curcumin content ranged from 1.41 % (IT10) to 4.16 % (IT1) with a mean of 2.97 %; essential oil content ranged from 4.04 % (Roma) to 6.44 % (IT2 and IT6) with a mean of 5.21 %; and oleoresin content ranged from 8.10 % (IT10) to 17.00 % (IT5) with a mean of 11.13 %. The coefficients of variation were 31.15 %, 16.88 % and 21.44 % for curcumin, essential oil and oleoresin, respectively, indicating that curcumin is the most variable and hence the most responsive quality trait to selection in this germplasm set. Accession IT1 exceeded the check Roma by 121.28 % for curcumin, while IT5 exceeded Roma by 97.67 % for oleoresin and surpassed even the superior check Suranjana by 24.09 % for the same trait. Trait association analysis revealed that curcumin was weakly and positively associated with oleoresin ($r=0.25$) but weakly negatively associated with essential oil ($r=-0.23$), implying that simultaneous improvement of all three traits requires independent, trait-specific selection rather than indirect selection. Accessions IT1 (high curcumin), IT2 and IT6 (high essential oil), IT5 (very high oleoresin) and IT3 (balanced superiority for all three traits) are identified as elite quality donors for the turmeric improvement programme of Chhattisgarh and the central Indian plateau.

Keywords: *Curcuma longa*, germplasm evaluation, curcumin, essential oil, oleoresin, quality traits, Chhattisgarh

1. Introduction

Turmeric (*Curcuma longa* L.; family Zingiberaceae; $2n = 3x = 63$) is a perennial, vegetatively propagated rhizomatous herb that has been cultivated in the Indian subcontinent for several millennia as a spice, a natural dye, a cosmetic ingredient and one of the cornerstones of the Ayurvedic and Siddha systems of medicine (Ravindran *et al.*, 2007; Prasath *et al.*, 2019) [17, 15]. India is the acknowledged centre of diversity of the genus *Curcuma*, the largest producer, consumer and exporter of turmeric in the world, and the custodian of the richest assembled germplasm of the crop, much of it maintained at the National Active Germplasm Site of ICAR-Indian Institute of Spices Research, Kozhikode, and at the centres of the All India Coordinated Research Project (AICRP) on Spices (Sasikumar, 2005; Dudekula *et al.*, 2022) [20, 6]. Because the crop is an obligate triploid that almost never sets seed, its genetic improvement is essentially confined to clonal selection from existing germplasm, sporadic mutation breeding and more recently, marker-assisted characterization of the clonal diversity already present in farmers' fields and germplasm repositories (Sasikumar, 2005; Ravindran *et al.*, 2024) [20, 18]. This biological constraint makes systematic evaluation of indigenous germplasm for economically decisive traits - above all the quality attributes of the cured rhizome - the single most important pre-breeding activity in turmeric.

The commercial and therapeutic value of turmeric rests on three groups of phytochemicals. The curcuminoids - curcumin, demethoxycurcumin and bisdemethoxycurcumin - are diarylheptanoid pigments that impart the characteristic deep-yellow to orange colour and account for most of the documented anti-inflammatory, antioxidant, antimutagenic and anticancer activities of the spice (Amalraj *et al.*, 2017; Hewlings and Kalman, 2017; Nelson *et al.*, 2017; Kotha and Luthria, 2019) [4, 7, 12, 8]. The oleoresin, obtained by solvent extraction of the cured rhizome, is the industrially traded form that carries both the colouring curcuminoids and the flavouring volatile fraction, and its recovery percentage determines the economics of the extraction industry (Ravindran *et al.*, 2007; Prasath *et al.*, 2019) [17, 15]. The essential oil, dominated by the sesquiterpenes α -turmerone, β -turmerone (curlone), contributes the aroma and possesses independent anti-inflammatory, antimicrobial and antioxidant activities (Dosoky and Setzer, 2018; Mishra *et al.*, 2018; Sharma *et al.*, 2022) [5, 11, 21]. International trade specifications, pharmaceutical buyers and the nutraceutical industry therefore price turmeric primarily on curcumin and oleoresin contents, and a difference of even one percentage point in curcumin translates into a substantial difference in farm-gate and export value (Soleimani *et al.*, 2018; Dudekula *et al.*, 2022) [25, 6].

A consistent finding of germplasm studies across India and elsewhere is that all three quality traits exhibit exceptionally wide genotypic variation. In the classical evaluation of 184 *Curcuma* accessions, Ratnambal (1986) [16] recorded striking ranges for curing percentage, essential oil, oleoresin and curcumin, a pattern repeatedly confirmed in subsequent decades. Screening of 60 genotypes by spectrophotometry revealed curcuminoid values ranging from 0.4 % to 8.8 % (Dudekula *et al.*, 2022) [6], while the recent large-scale characterization of 200 Indian accessions at Tamil Nadu Agricultural University recorded curcumin from 0.41 % to 2.17 % and total curcuminoids from 1.26 % to 4.55 % (Dudekula *et al.*, 2022) [6]. Pal *et al.*, (2020) [13], working with genotypes from the sub-Himalayan terai, and Sandeep *et al.*, (2016) [19], profiling collections across the agroclimatic zones of Odisha, demonstrated that both the genotype and the production environment structure this chemical diversity. Singh *et al.*, (2013) [24] showed that elite, drug-yielding types can be identified only through agroclimatic-zone-based evaluation, because genotype $\times$ environment interaction is strong for these traits - a conclusion reinforced by the recent comparison of turmeric performance across field, greenhouse and vertical production systems (Silaru *et al.*, 2024) [23].

Chhattisgarh, located on the central Indian plateau, is an emerging turmeric-growing state whose tribal-dominated rainfed tracts Harbour distinctive, locally adapted indigenous material that remains poorly characterized for quality. The AICRP on Spices centre at the College of Agriculture and Research Station (CARS), Raigarh, has assembled fifty-four indigenous accessions and has recently contributed the released varieties Chhattisgarh Haldi-1 (IT-2), Chhattisgarh Haldi-2 (IT-10) and CG Raigarh Haldi-3 (IT-36) to the state's varietal portfolio. However, a systematic, replicated evaluation of this regional germplasm against the established national checks Roma and Suranjana for the three commercially decisive quality traits has not been reported. The pharmacological prominence of curcumin has transformed turmeric from a culinary

commodity into a strategic medicinal crop. Curcumin is among the most intensively investigated natural products of the past two decades, with documented anti-inflammatory, antioxidant, anticancer, antidiabetic, cardioprotective and neuroprotective activities and an exceptional safety record in human studies (Hewlings and Kalman, 2017; Nelson *et al.*, 2017; Amalraj *et al.*, 2017; Soleimani *et al.*, 2018) [7, 12, 4, 25]. Although its poor aqueous solubility and rapid metabolism limit oral bioavailability, the development of highly bioavailable formulations has sustained industrial demand for curcumin-rich raw material and standardized extracts (Lopresti, 2018; Stohs *et al.*, 2020; Kotha and Luthria, 2019) [9, 26, 8]. Parallel interest surrounds the volatile fraction: turmerone-rich essential oils have demonstrated anti-inflammatory, antimicrobial, antifungal and antioxidant activities, and the aroma profile of the oil determines the acceptability of turmeric in the flavour and fragrance industries (Dosoky and Setzer, 2018; Mishra *et al.*, 2018) [5, 11]. Since neither the pigment nor the volatile fraction can be economically synthesized at the farm level, both must be secured through genetics - that is, through the identification and deployment of naturally high-chemotype clones from the indigenous germplasm pool.

The economics of turmeric are increasingly quality-driven. India accounts for the overwhelming share of global production and export of turmeric and turmeric-derived products, and the demand for curcumin-rich rhizomes, standardized oleoresins and turmerone-rich oils from the food, nutraceutical, cosmetic and pharmaceutical industries has been expanding steadily (Ravindran *et al.*, 2007; Soleimani *et al.*, 2018; Stohs *et al.*, 2020) [17, 25, 26]. Within this value chain, quality evaluation of germplasm serves two distinct but complementary purposes: it identifies donor clones for breeding, and it identifies region-specific planting material whose superior chemistry can itself become a marketable identity - a geographical and varietal brand - for the farming communities that conserve it. For a state like Chhattisgarh, where turmeric is cultivated largely by smallholders under rainfed conditions, even modest gains in curcumin or oleoresin content translate directly into proportionate gains in the value of the same produce without any increase in input cost, which makes quality-oriented germplasm evaluation arguably the highest-return research investment available for the crop in the region.

The present investigation was therefore undertaken with the objectives of

- 1) Quantifying the variability for curcumin, essential oil and oleoresin contents among elite indigenous accessions of Chhattisgarh;
- 2) Benchmarking the accessions against the national and local checks; and
- 3) Identifying trait-specific and balanced-quality donors for the turmeric quality improvement programme of the central Indian plateau.

2. Materials and Methods

2.1 Experimental site and season

The field experiment was conducted at the Research Farm of the All India Coordinated Research Project on Spices, College of Agriculture and Research Station, Raigarh, Chhattisgarh, India, during two consecutive *Kharif* seasons, 2021-2022 and 2022-2023. Raigarh lies in the Chhattisgarh plains agroclimatic zone of the central Indian plateau and is characterized by a sub-humid tropical climate with hot

summers, a monsoon period concentrated between June and September, and mild, dry winters. The soil of the experimental farm is an inceptisol typical of the region, with a light-to-medium texture suited to rhizomatous spice crops.

2.2 Plant material and experimental design

The experimental material comprised fifty-four indigenous accessions of turmeric assembled at the AICRP on Spices centre, together with the national and local checks viz., Roma, Suranjana, BSR-2, Chhattisgarh Haldi-1 (IT-2), Chhattisgarh Haldi-2 (IT-10) and CG Raigarh Haldi-3 (IT-36). The trial was laid out in a Randomized Complete Block Design (RBD) with two replications. Each genotype was grown in a plot of 3 m × 1 m at a spacing of 30 cm × 20 cm. The recommended package of practices for the late-sown crop of the zone - land preparation, planting of healthy finger rhizomes, nutrient management, irrigation, mulching, earthing-up and plant protection - was followed uniformly across all plots to raise a healthy crop and to minimize non-genetic sources of variation.

2.3 Curing and sample preparation

Rhizomes were harvested at full maturity, when the aerial shoots had dried completely. Representative rhizome samples from each plot were washed, sliced, boiled/steamed as per the standard curing procedure, dried to a safe moisture level and ground to a uniform powder. The cured, powdered samples were stored in airtight, moisture-proof containers at ambient laboratory conditions until chemical analysis.

2.4 Estimation of quality parameters

Quality analyses were performed on the ten most promising accessions identified from the field evaluation (IT1, IT2, IT3, IT5, IT6, IT10, IT30, IT31, IT33 and IT36) together with the two principal checks, Roma and Suranjana.

Curcumin content was estimated by the standard spectrophotometric method. A known weight of cured turmeric powder was extracted with acetone/alcohol until complete exhaustion of the pigment, the extract was filtered and made to a known volume, and the absorbance of the clear yellow solution was read on a UV-visible spectrophotometer at the wavelength of maximum absorption of curcumin (≈ 425 nm). Curcumin percentage was computed from the absorbance, the volume made up, the dilution and the weight of the sample, using the standard absorptivity value of curcumin, following the spectrophotometric procedure widely adopted for turmeric quality screening (Paramasivam *et al.*, 2009; Dudekula *et al.*, 2022) [14, 6]. Analyses were performed in replicate and mean values are reported.

Essential oil content was determined by hydro-distillation. A known weight of cured powder was distilled with water in a Clevenger-type apparatus for several hours until no further increase in the oil layer was observed. The volume of oil collected in the graduated trap was recorded after allowing the apparatus to cool, and the oil content was expressed as percentage on a dry-weight basis, in accordance with the

established pharmacopoeial procedure for volatile-oil estimation in turmeric (Mishra *et al.*, 2018; Sharma *et al.*, 2022) [11, 21].

Oleoresin content was estimated by exhaustive solvent extraction. A known weight of cured powder was extracted with acetone in a Soxhlet apparatus until the siphonate ran colourless, the solvent was recovered under reduced pressure, and the residual oleoresin was dried to constant weight and expressed as percentage of the dry sample weight (Ratnambal, 1986; Ravindran *et al.*, 2007) [16, 17].

The above quality analysis was achieved with the collaboration of Indian Institute of Spices Research, Kozhikode, Kerala, India

2.5 Quality benchmarks and reference standards

The estimated values were interpreted against the quality benchmarks used in the Indian and international trade of turmeric: curcumin contents above 3 % are considered desirable for pharmaceutical-grade raw material, while released Indian varieties typically range between 2 % and 5 % curcumin; essential oil contents of 4-7 % and oleoresin recoveries of 8-15 % span the range reported for commercial germplasm (Ratnambal, 1986; Ravindran *et al.*, 2007; Prasath *et al.*, 2019; Silaru *et al.*, 2024) [16, 17, 15, 23]. The national check Roma and the high-quality check Suranjana served as the internal experimental benchmarks against which the accessions were judged.

2.6 Statistical analysis

Data were compiled as pooled estimates over the two seasons for each genotype. Descriptive statistics - mean, minimum, maximum, range and standard deviation (SD) - were computed for each quality trait, and the coefficient of variation (CV, %) was derived as the ratio of the standard deviation to the mean. Per cent superiority of each accession over the check varieties Roma and Suranjana was calculated as: superiority (%) = [(genotype value - check value)/check value] × 100. Pearson's product-moment correlation coefficients were computed among the three quality traits across the twelve genotypes to examine trait associations relevant to simultaneous selection. Graphical presentations - comparative bar charts, ranked performance charts, scatter plots with fitted trends, the correlation heat map and distribution plots - were prepared from the same data set. The experimental design and analytical framework follow the standard approaches recommended for germplasm evaluation in clonally propagated spice crops (Ratnambal, 1986; Sasikumar, 2005; Dudekula *et al.*, 2022) [16, 20, 6].

3. Results

3.1 Variability for curcumin, essential oil and oleoresin contents

The estimation of the three quality parameters in the ten elite indigenous accessions and the two checks is presented in Table 1 and visualized in Figure 1. All three traits exhibited wide and clearly genotypic variation among the entries.

Table 1: Estimation of quality parameters in selected genotypes of turmeric (*Curcuma longa* L.)

Sl. No.	Genotype	Curcumin (%)	Essential oil (%)	Oleoresin (%)
1.	IT1	4.16	4.29	11.15
2.	IT2	1.44	6.44	11.60
3.	IT3	3.67	6.11	12.30

4.	IT5	2.99	4.39	17.00
5.	IT6	3.26	6.44	10.35
6.	IT10	1.41	5.65	8.10
7.	IT30	3.98	5.12	10.50
8.	IT31	3.51	4.29	10.35
9.	IT33	3.37	4.95	9.70
10.	IT36	2.95	4.85	10.25
11.	Roma (Check)	1.88	4.04	8.60
12.	Suranjana (Check)	3.05	5.94	13.70

Bold values indicate the maximum recorded for the respective trait

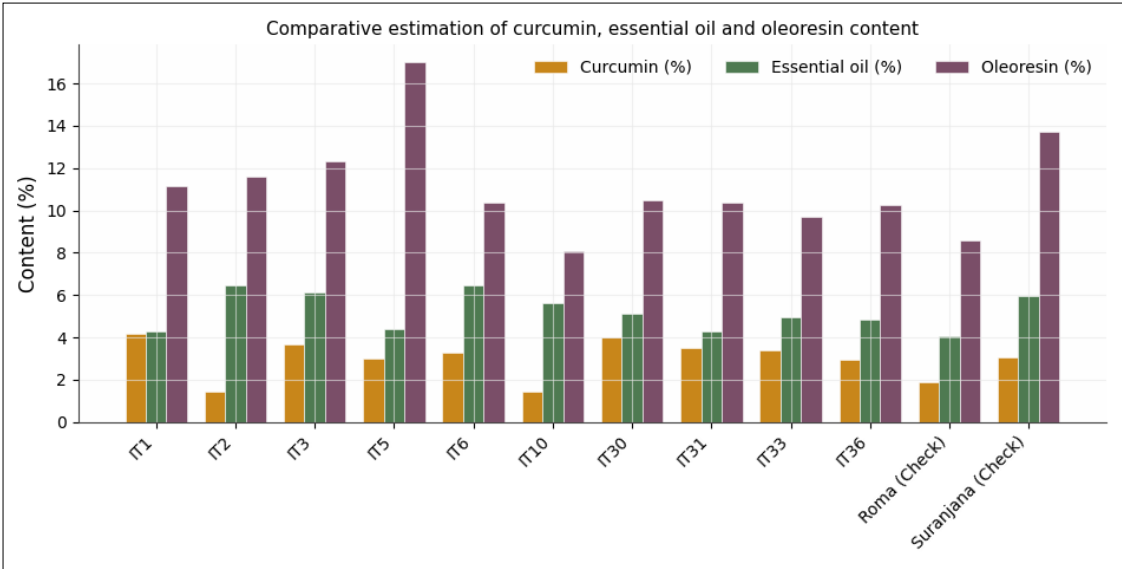


Fig 1: Comparative estimation of curcumin, essential oil and oleoresin content among selected turmeric genotypes (checks shown alongside indigenous accessions)

Curcumin content varied nearly three-fold, from 1.41 % in IT10 to 4.16 % in IT1 (Figure 2a). Three accessions - IT1 (4.16 %), IT30 (3.98 %) and IT3 (3.67 %) - exceeded the superior check Suranjana (3.05 %), and seven of the ten accessions surpassed the national check Roma (1.88 %). Essential oil content ranged from 4.04 % in Roma to 6.44

%, a value shared by IT2 and IT6; IT3 (6.11 %) also exceeded Suranjana (5.94 %) for this trait (Figure 2b). Oleoresin content showed the widest absolute spread, from 8.10 % in IT10 to an exceptional 17.00 % in IT5, which was the only entry to surpass Suranjana (13.70 %) for oleoresin recovery (Figure 2c).

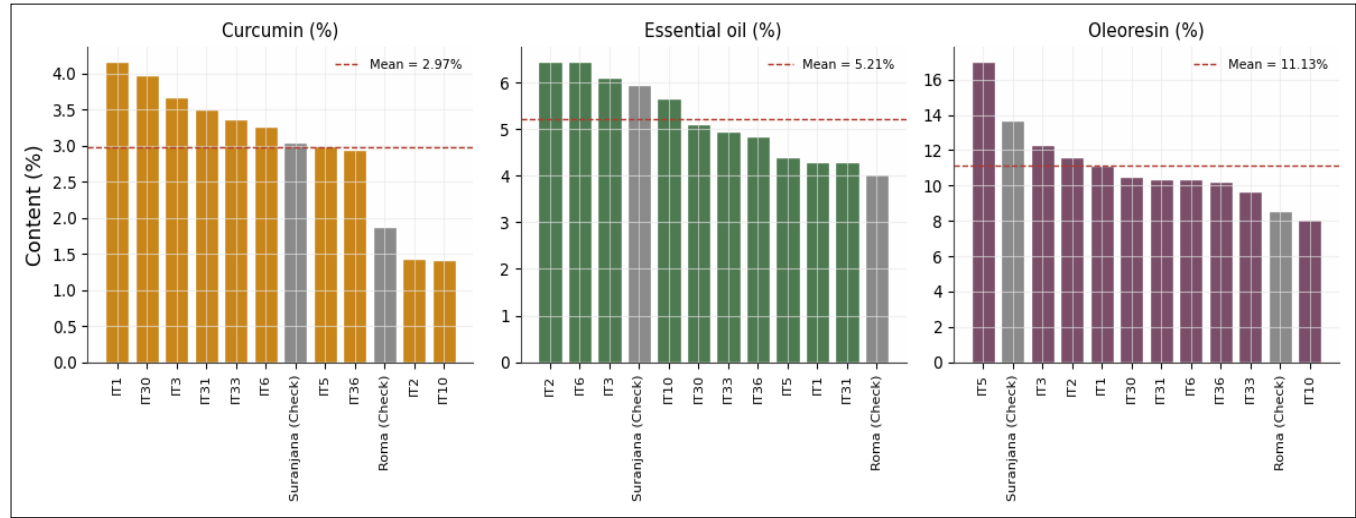


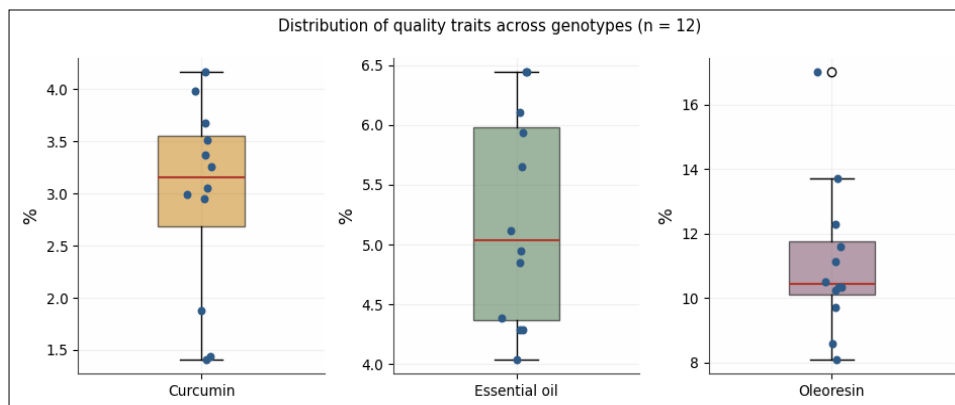
Fig 2: Ranked performance of genotypes for (a) curcumin, (b) essential oil and (c) oleoresin content; grey bars denote check varieties and the dashed red line indicates the respective grand mean

3.2 Descriptive statistics and extent of variability
The descriptive statistics for the three traits (Table 2;

distribution in Figure 3) quantify the magnitude of exploitable variability in the germplasm set.

Table 2: Descriptive statistics of quality parameters across the twelve genotypes evaluated

Parameter	Mean (%)	Minimum (%)	Maximum (%)	Range	SD	CV (%)
Curcumin	2.97	1.41	4.16	2.75	0.93	31.15
Essential oil	5.21	4.04	6.44	2.40	0.88	16.88
Oleoresin	11.13	8.10	17.00	8.90	2.39	21.44

**Fig 3:** Box-and-whisker distribution of the three quality traits across the twelve genotypes; the red line marks the median and blue points are individual genotypes

The coefficient of variation was highest for curcumin (31.15 %), followed by oleoresin (21.44 %) and essential oil (16.88 %). The range for oleoresin (8.90 percentage points) was more than three times that of curcumin (2.75 points) and essential oil (2.40 points). Both statistics indicate that the germplasm contains ample additive scope for selection, and that curcumin - the trait of highest commercial value - is

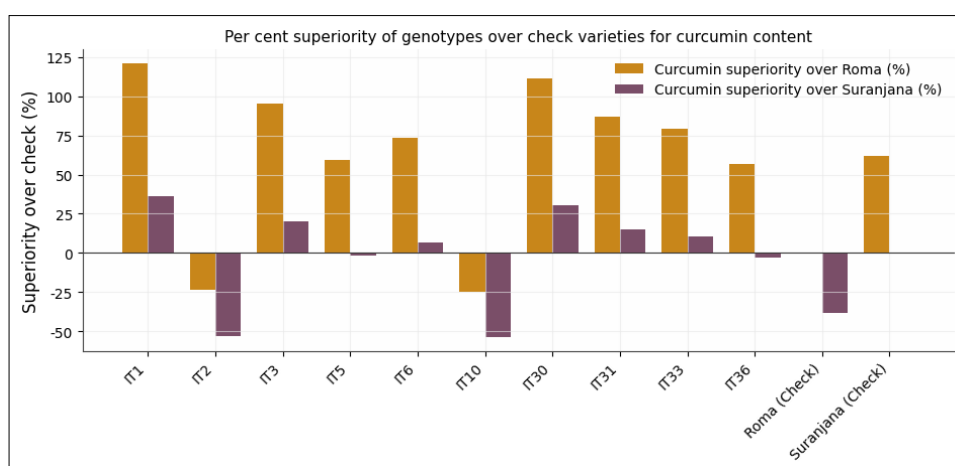
also the most variable and therefore potentially the most responsive to selection in this material.

3.3 Benchmarking against check varieties

The per se performance of the accessions relative to the two checks is summarized in Table 3, and the per cent superiority for curcumin over each check is depicted in Figure 4.

Table 3: Comparison of elite accessions with the check varieties and their quality superiority

Genotype	Curcumin (%)	Essential oil (%)	Oleoresin (%)	Quality superiority
IT1	4.16	4.29	11.15	High curcumin
IT2	1.44	6.44	11.60	High essential oil
IT3	3.67	6.11	12.30	High overall quality
IT5	2.99	4.39	17.00	Highest oleoresin
IT6	3.26	6.44	10.35	High essential oil
IT10	1.41	5.65	8.10	-
IT30	3.98	5.12	10.50	High curcumin
IT31	3.51	4.29	10.35	High curcumin
IT33	3.37	4.95	9.70	Moderate-high curcumin
IT36	2.95	4.85	10.25	-
Roma (Check)	1.88	4.04	8.60	Check
Suranjana (Check)	3.05	5.94	13.70	Superior check

**Fig 4:** Per cent superiority of the genotypes over the checks Roma and Suranjana for curcumin content

The superiority analysis (Table 4) shows that relative to Roma, accession IT1 recorded 121.28 % higher curcumin, IT30 111.70 % and IT3 95.21 %; IT2 and IT6 recorded 59.41 % higher essential oil; and IT5 recorded 97.67 % higher oleoresin. Relative to the stronger check Suranjana, IT1 (36.39 %) and IT30 (30.49 %) were still markedly

superior for curcumin, IT2 and IT6 (8.42 %) for essential oil, and IT5 (24.09 %) for oleoresin. IT3 combined above-Suranjana levels of curcumin (+20.33 %) and essential oil (+2.86 %) with a high oleoresin content (12.30 %), and is therefore the most balanced high-quality accession in the set.

Table 4: Per cent superiority (+) or inferiority (-) of genotypes over the check varieties for the three quality traits

Genotype	Curcumin over Roma	Curcumin over Suranjana	Essential oil over Roma	Essential oil over Suranjana	Oleoresin over Roma	Oleoresin over Suranjana
IT1	+121.28	+36.39	+6.19	-27.78	+29.65	-18.61
IT2	-23.40	-52.79	+59.41	+8.42	+34.88	-15.33
IT3	+95.21	+20.33	+51.24	+2.86	+43.02	-10.22
IT5	+59.04	-1.97	+8.66	-26.09	+97.67	+24.09
IT6	+73.40	+6.89	+59.41	+8.42	+20.35	-24.45
IT10	-25.00	-53.77	+39.85	-4.88	-5.81	-40.88
IT30	+111.70	+30.49	+26.73	-13.80	+22.09	-23.36
IT31	+86.70	+15.08	+6.19	-27.78	+20.35	-24.45
IT33	+79.26	+10.49	+22.52	-16.67	+12.79	-29.20
IT36	+56.91	-3.28	+20.05	-18.35	+19.19	-25.18

3.4 Association among quality traits

Scatter plots and the correlation matrix (Figures 5 and 6) revealed that the three quality traits are essentially independent of one another in this germplasm. Curcumin

and oleoresin were weakly positively associated ($r=0.25$), curcumin and essential oil were weakly negatively associated ($r=-0.23$), and essential oil and oleoresin were virtually uncorrelated ($r=0.03$).

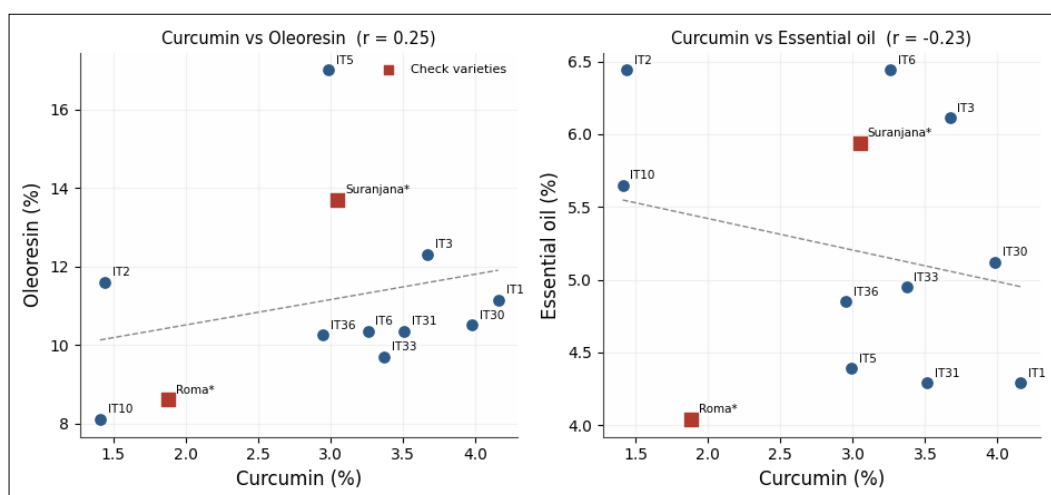


Fig 5: Scatter relationships of curcumin with oleoresin (left) and with essential oil (right); check varieties are shown as red squares and the dashed line is the fitted linear trend

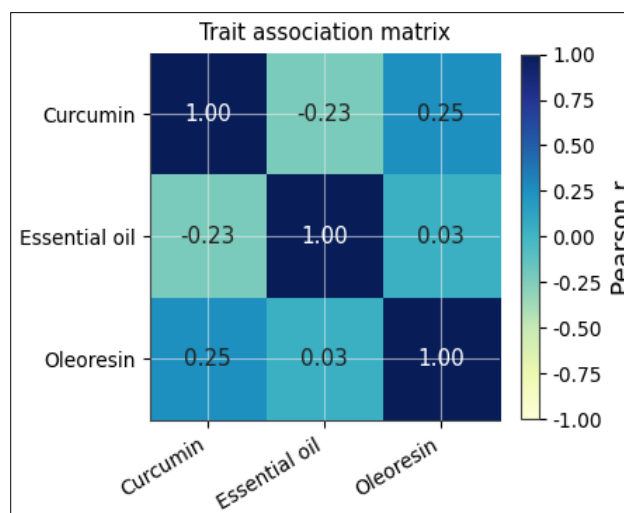


Fig 6: Pearson correlation (r) matrix among the three quality traits across the twelve genotypes

The practical consequence of these weak associations is visible in the data themselves: IT1 combines the highest curcumin with only moderate essential oil and oleoresin; IT5 combines the highest oleoresin with average curcumin and below-average essential oil; and IT2 and IT6 combine the highest essential oil with low-to-average curcumin. No single accession is superior for all three traits simultaneously, confirming that trait-specific donors, rather than indirect selection, must anchor the quality breeding programme.

3.5 Accession-wise quality profiles

Read individually, each elite accession presents a distinct quality identity with direct implications for its end use. IT1 recorded the highest curcumin content of the entire set (4.16 %) - 121.28 % above Roma and 36.39 % above Suranjana - while holding average levels of essential oil (4.29 %) and oleoresin (11.15 %); it is, therefore, a specialist pigment donor whose value lies almost entirely in its exceptional colouring and pharmaceutical-grade curcumin fraction. IT30, with the second-highest curcumin (3.98 %), followed the same specialist pattern but with a better essential oil level (5.12 %), making it the second pillar of the high-curcumin donor group. IT3 emerged as the most balanced accession of the experiment: curcumin 3.67 % (third highest), essential oil 6.11 % (third highest) and oleoresin 12.30 % (second highest among accessions), a combination matched by no other entry and superior to the check

Suranjana for two of the three traits. IT5 is the outstanding oleoresin type of the set (17.00 %), exceeding Suranjana by 24.09 % and nearly doubling Roma, while maintaining an average curcumin content (2.99 %); its oleoresin advantage of 4.70 percentage points over the next-best accession (IT3, 12.30 %) is of a magnitude rarely encountered in germplasm screens. IT2 and IT6 constitute the essential-oil specialists, both recording 6.44 % oil - the maximum of the set and 8.42 % above Suranjana - although IT2 carries the second-lowest curcumin content (1.44 %), whereas IT6 combines its high oil with an above-average curcumin level (3.26 %) and is therefore the more useful of the two for dual-purpose selection. IT31 (3.51 %) and IT33 (3.37 %) form a mid-high curcumin cluster with moderate oil and oleoresin, both clearly superior to Roma for all three traits. IT36 (the released CG Raigarh Haldi-3) recorded near-mean values for curcumin (2.95 %), oil (4.85 %) and oleoresin (10.25 %), consistent with its identity as a balanced agronomic variety rather than a quality specialist. IT10 (Chhattisgarh Haldi-2) occupied the bottom of the elite panel for curcumin (1.41 %) and oleoresin (8.10 %), although its essential oil content (5.65 %) remained above the grand mean. Finally, the contrast between the two checks - Roma (1.88 % curcumin) and Suranjana (3.05 % curcumin, 13.70 % oleoresin) - bracketed the test entries between a low-quality and a high-quality national standard and confirmed the discriminating efficiency of the evaluation.

Table 6: Elite quality donors identified from the indigenous turmeric germplasm of Chhattisgarh

Donor category	Accession	Decisive value	Superiority over Roma	Superiority over Suranjana	Target end use
High curcumin	IT1	4.16 %	+121.28 %	+36.39 %	Pharmaceutical/nutraceutical pigment
High curcumin	IT30	3.98 %	+111.70 %	+30.49 %	Pharmaceutical/nutraceutical pigment
Balanced quality	IT3	3.67 % curcumin; 6.11 % oil; 12.30 % oleoresin	+95.21 % (curcumin)	+20.33 % (curcumin)	All-round quality cultivation
High essential oil	IT2	6.44 %	+59.41 %	+8.42 %	Flavour, fragrance and oil therapeutics
High essential oil	IT6	6.44 % (with 3.26 % curcumin)	+59.41 %	+8.42 %	Dual-purpose oil-curcumin selection
High oleoresin	IT5	17.00 %	+97.67 %	+24.09 %	Solvent-extraction and colour industry

3.6 Performance of the present germplasm in the national context

To place the accessions in perspective, the extremes and

means of the present set were compared with published evaluations of Indian turmeric germplasm conducted under comparable field conditions (Table 5).

Table 5: Comparison of the present findings with published evaluations of Indian turmeric germplasm

References	Germplasm evaluated	Curcumin (%)	Essential oil (%)	Oleoresin (%)
Present study (Raigarh, C.G.)	10 accessions + 2 checks	1.41-4.16 (mean 2.97)	4.04-6.44 (mean 5.21)	8.10-17.00 (mean 11.13)
Dudekula <i>et al.</i> , (2022) ^[6] , TNAU, Coimbatore	200 accessions	0.41-2.17	-	-
Vinodhini <i>et al.</i> , (2019) ^[28] , Tamil Nadu	55 genotypes	up to 2.79	-	-
Shashidhar <i>et al.</i> , (2018) ^[22] , Karnataka	20 genotypes	up to 4.23	2.03-6.50	8.01-11.35
Silaru <i>et al.</i> , (2024) ^[23] , Kerala (field)	21 genotypes	Significant genotypic variation	Significant genotypic variation	Significant genotypic variation
Ratnambal (1986) ^[16] , Kerala	184 accessions	Wide variation	Wide variation	Wide variation

The comparison shows that the upper bounds recorded in the Chhattisgarh germplasm for essential oil (6.44 %) and oleoresin (17.00 %) meet or exceed the upper bounds reported from the larger national panels, while the curcumin maximum (4.16 %) is comparable to that of the best released varieties evaluated elsewhere (4.08-4.23 %; Shashidhar *et al.*, 2018) ^[22]. The mean curcumin content of the present set (2.97 %) is distinctly higher than the grand mean of the 200-accession southern panel (1.38 %; Dudekula *et al.*, 2022) ^[6], which is partly attributable to the fact that the present set represents a pre-selected elite subset

of a larger fifty-four-accession field trial rather than an unselected germplasm collection.

4. Discussion

4.1 Magnitude and pattern of variability in the Chhattisgarh germplasm

The nearly three-fold range in curcumin (1.41-4.16 %) and the more than two-fold range in oleoresin (8.10-17.00 %) recorded in the present set of Chhattisgarh accessions fall squarely within, and at the upper end exceed, the variability reported from the major Indian germplasm evaluations.

Ratnambal (1986) ^[16], in the classical screening of 184 *Curcuma* accessions, was the first to demonstrate that curing percentage, essential oil, oleoresin and curcumin all vary widely in the Indian germplasm; the present results confirm that this reservoir of variability persists in the indigenous material of the central Indian plateau. The mean curcumin content of the present set (2.97 %) compares favourably with the grand means reported from large southern Indian panels - 1.38 % for curcumin across 200 accessions at TNAU, Coimbatore (Dudekula *et al.*, 2022) ^[6] and 2.79 % for the best genotype in the fifty-five-genotype evaluation at Tamil Nadu (Vinodhini *et al.*, 2019) ^[28] - while the maximum value recorded here (IT1, 4.16 %) is comparable to the curcumin levels of the leading released varieties CO-2 (4.23 %) and BSR-3 (4.08 %) reported from Tamil Nadu and Karnataka conditions (Shashidhar *et al.*, 2018; Vinodhini *et al.*, 2019) ^[22, 28]. This places IT1 among the high-curcumin types of the country and marks it as a genuine national-level quality donor rather than merely a locally superior line.

The essential oil range of 4.04-6.44 % is high by national standards: Shashidhar *et al.*, (2018) ^[22] reported 2.03-6.50 % across genotypes in the northern dry zone of Karnataka, and the values recorded in the sub-Himalayan terai and Odisha collections were generally lower on a dry-rhizome basis (Sandeep *et al.*, 2016; Pal *et al.*, 2020) ^[19, 13]. The twin high-oil accessions IT2 and IT6 (6.44 %) are thus close to the upper bound of the published Indian range. Similarly, the oleoresin recovery of 17.00 % in IT5 is exceptional; published evaluations of Indian germplasm typically report oleoresin in the 8-13 % band (Ratnambal, 1986; Silaru *et al.*, 2024) ^[16, 23], and even the superior check Suranjana - itself one of the highest-oleoresin released varieties of the country - reached only 13.70 % under the same conditions.

4.2 Curcumin as the most responsive trait to selection

The coefficient of variation observed for curcumin (31.15 %) was nearly double that of essential oil (16.88 %) and half again that of oleoresin (21.44 %). High variability for curcumin has been a recurrent observation: Dudekula *et al.*, (2022) ^[6] reported a CV of 24.31 % for curcumin across 200 accessions, Verma *et al.*, (2014) ^[27] and Vithya *et al.*, (2021) ^[29] recorded high coefficients of variation for rhizome and quality traits in eastern and southern Indian panels, and Aarthi *et al.*, (2018) ^[1] demonstrated that curcumin varies sufficiently among genotypes to permit effective direct selection. Because turmeric is a sterile triploid, the entire breeding strategy reduces to identifying and multiplying superior clones (Sasikumar, 2005) ^[20]; a high CV for the trait of maximum commercial value therefore represents the most favourable possible precondition for clonal selection in this germplasm. The mechanism underlying this variability is genotypic rather than accidental: curcuminoid accumulation in the rhizome is governed by the expression of the phenylpropanoid/diketide biosynthetic pathway, which is under strong genetic control, although its quantitative expression is modulated by soil organic carbon, available nitrogen, manganese and agroclimatic factors (Singh *et al.*, 2013; Sandeep *et al.*, 2016) ^[24, 19]. The wide range recorded here under a single, uniform environment - identical design, spacing, package of practices and season - indicates that the differences among accessions are predominantly genetic, consistent with the conclusion of Singh *et al.*, (2013) ^[24] that under uniform agroclimate the

variation in phytoconstituents reflects differential expression of biosynthetic genes.

4.3 Benchmarking against the checks and its breeding implication

A germplasm evaluation acquires practical meaning only when benchmarked against varieties that farmers actually grow. Roma, the national check, is a low-curcumin, low-oleoresin variety, and most of the test accessions exceeded it for all three traits - an expected result that chiefly validates the discriminating power of the experiment. The more stringent benchmark is Suranjana, one of the country's finest quality varieties. That three accessions (IT1, IT30, IT3) exceeded Suranjana for curcumin, two (IT2, IT6) exceeded it for essential oil, and one (IT5) exceeded it for oleoresin demonstrates that the Chhattisgarh indigenous material contains clones equal or superior to the best released varieties for each individual trait. Particularly noteworthy is IT5, whose oleoresin content of 17.00 % represents a 24.09 % superiority over Suranjana and a 97.67 % superiority over Roma; for the solvent-extraction and colour industries, in which oleoresin recovery is the primary determinant of raw-material value (Ravindran *et al.*, 2007; Prasath *et al.*, 2019) ^[17, 15], IT5 is an outstanding find. Conversely, IT10 (the released Chhattisgarh Haldi-2) was the lowest entry for both curcumin (1.41 %) and oleoresin (8.10 %) in this elite subset, indicating that its release value rests on agronomic attributes other than rhizome chemistry and that the newly characterized accessions offer scope to lift the quality ceiling of the state's varietal portfolio.

4.4 Independence of the quality traits and consequences for simultaneous improvement

The weak correlations among curcumin, essential oil and oleoresin ($r=0.25$, -0.23 and 0.03 , respectively) are in line with earlier association studies in turmeric, which have generally found curcumin content to be independent of, or only weakly associated with, yield and other quality components (Aarthi *et al.*, 2018; Dudekula *et al.*, 2022) ^[1, 6]. Biochemically this independence is plausible: the curcuminoids are phenylpropanoid-derived diarylheptanoids, whereas the essential oil fraction consists of mevalonate-pathway sesquiterpenes (α -turmerone, α - and β -turmerone) and monoterpenes (Dosoky and Setzer, 2018; Kotha and Luthria, 2019) ^[5, 8]. The two biosynthetic systems draw on distinct precursor pools and are regulated separately during rhizome development, so a clone can accumulate pigment without proportionately accumulating volatile oil - exactly the pattern shown by IT1 (highest curcumin, moderate oil) and IT2 (highest oil, lowest-but-one curcumin). Oleoresin, being the composite solvent extract that contains both the pigments and the volatiles, shows a slight positive tendency with curcumin because curcuminoids constitute the bulk of the extract, but the association is too weak to be of predictive value. The breeding implication is unequivocal: quality improvement in turmeric must proceed through trait-specific donor lines followed by evaluation of their combinations, rather than through indirect selection on any single trait. In this framework, IT1 and IT30 serve as curcumin donors, IT2 and IT6 as essential-oil donors, IT5 as the oleoresin donor, and IT3 as the balanced-quality line suitable for direct multi-trait deployment where the market demands all-round quality.

4.5 Environmental context and the case for multi-location validation

Genotype $\times$ environment interaction is a well-established feature of turmeric quality traits. Curcumin content of the same variety differs across locations and production systems (Sandeep *et al.*, 2016; Silaru *et al.*, 2024) ^[19, 23], and agroclimatic-zone-based evaluation has been explicitly recommended as a prerequisite for quality breeding (Singh *et al.*, 2013) ^[24]. The field environment of the Chhattisgarh plains, with its sub-humid monsoon climate, appears congenial to quality expression: the grand means recorded here (curcumin 2.97 %, essential oil 5.21 %, oleoresin 11.13 %) are at the higher end of published national means, echoing the finding of Silaru *et al.*, (2024) ^[23] that open-field conditions favour the accumulation of oleoresin, essential oil and curcuminoids relative to protected systems. Nevertheless, because the present estimates derive from a single location over two seasons, the elite accessions identified should be advanced to multi-location trials across the agroclimatic zones of Chhattisgarh and the AICRP on Spices network to establish their stability before varietal proposal - the same pipeline through which the centre's earlier releases, Chhattisgarh Haldi-1, Chhattisgarh Haldi-2 and CG Raigarh Haldi-3, were developed.

4.6 Methodological considerations in quality estimation

The values reported here were obtained with the classical spectrophotometric (curcumin), Clevenger hydro-distillation (essential oil) and Soxhlet solvent-extraction (oleoresin) methods that remain the workhorse procedures of spice quality laboratories and of the Indian trade. It is worth noting that spectrophotometric curcumin estimates, which quantify total light-absorbing curcuminoid pigment at ~425 nm, tend to read higher than chromatographic estimates of pure curcumin. Dudekula *et al.*, (2022) ^[6], analysing the same accessions by HPTLC and UHPLC, obtained systematically lower UHPLC values and attributed the difference to the ultra-high sensitivity of the chromatographic system; Paramasivam *et al.*, (2009) ^[14] and Chao *et al.*, (2018) ^[2] have likewise emphasized the superior resolution of HPTLC and HPLC-based quantification of individual curcuminoids. The absolute values of the present study should therefore be read in the spectrophotometric convention that is standard in Indian germplasm catalogues, while the relative ranking of genotypes - the output that matters for selection - has repeatedly been shown to be robust across estimation methods (Paramasivam *et al.*, 2009; Dudekula *et al.*, 2022) ^[14, 6]. Chromatographic confirmation of the individual curcuminoid profile (curcumin, demethoxycurcumin and bisdemethoxycurcumin) of the elite accessions identified here is a logical next step, since demethoxy- and bisdemethoxycurcumin possess distinct stability and bioactivity profiles of pharmaceutical interest (Hatamipour *et al.*, 2019; Kotha and Luthria, 2019) ^[3, 8].

4.7 Industrial, pharmaceutical and regional relevance

The identification of quality donors has direct economic significance for Chhattisgarh, where turmeric is an important cash crop of smallholder and tribal farmers in rainfed upland situations. Curcumin-based pricing is increasingly adopted by traders and pharmaceutical buyers (Dudekula *et al.*, 2022) ^[6], and the documented pharmacological credentials of curcumin - anti-inflammatory, antioxidant, anticancer and antidiabetic

activities with an excellent safety profile (Amalraj *et al.*, 2017; Nelson *et al.*, 2017; Soleimani *et al.*, 2018; Lopresti, 2018; Stohs *et al.*, 2020) ^[4, 12, 25, 9, 26] - continue to expand global demand for high-curcumin raw material. High-oleoresin types such as IT5 serve the colour-extraction and food-ingredient industry, while high-oil clones such as IT2 and IT6 address the aroma, flavour and essential-oil therapeutics segment in which turmerone-rich oils have demonstrated anti-inflammatory, antimicrobial and antioxidant activities (Mishra *et al.*, 2018; Dosoky and Setzer, 2018; Sharma *et al.*, 2022) ^[11, 5, 21]. Complementary molecular characterization of these quality donors with SSR and other markers, as demonstrated for Indian turmeric germplasm by Ravindran *et al.*, (2024) ^[18], would protect their identity, enable distinctness testing for variety registration under the Protection of Plant Varieties and Farmers' Rights Authority, and accelerate their use in the national improvement programme.

4.8 Limitations and future directions

The strengths of the present study - a replicated two-season field trial, uniform agronomy, and benchmarking against two national checks - are tempered by limitations that define the immediate research agenda. First, quality estimation was confined to the ten most promising accessions of the fifty-four-accession field trial; extending the chemical analysis to the entire set would allow formal estimation of variance components, heritability in the broad clonal sense, and genetic advance for the quality traits. Second, the single-location design does not separate genotypic from genotype $\times$ environment effects, and multi-location testing across the agroclimatic zones of Chhattisgarh is required before the elite clones are proposed for release, as recommended for quality-oriented turmeric breeding (Singh *et al.*, 2013; Silaru *et al.*, 2024) ^[24, 23]. Third, spectrophotometric curcumin values should be confirmed by HPTLC/UHPLC profiling of the individual curcuminoids, and the essential oils of IT2 and IT6 should be subjected to GC-MS characterization to establish their turmerone profiles, which determine their therapeutic and aromatic value (Mishra *et al.*, 2018; Chao *et al.*, 2018; Sharma *et al.*, 2022) ^[11, 2, 21]. Fourth, molecular fingerprinting of the donor lines with SSR markers (Ravindran *et al.*, 2024) ^[18] would secure their identity for variety registration and intellectual-property protection. Finally, coupling the quality data with rhizome yield and dry recovery from the same trial will permit computation of curcumin yield per hectare - the economically decisive composite trait, since curcumin yield is the product of rhizome yield and curcumin concentration (Miyazaki *et al.*, 2014; Dudekula *et al.*, 2022) ^[10, 6] - and hence a complete merit ranking of the germplasm for both farmers and industry.

5. Conclusion

The evaluation of elite indigenous turmeric accessions of Chhattisgarh against the national and local checks revealed wide, commercially exploitable variability for all three decisive quality traits of the cured rhizome. Curcumin ranged from 1.41 % to 4.16 % (CV 31.15 %), essential oil from 4.04 % to 6.44 % (CV 16.88 %) and oleoresin from 8.10 % to 17.00 % (CV 21.44 %). Accession IT1 (curcumin 4.16 %; 36.39 % superior to Suranjana), IT30 (3.98 %) and IT3 (3.67 % curcumin with 6.11 % oil and 12.30 % oleoresin) emerged as high-curcumin and balanced-quality

types; IT2 and IT6 as high-essential-oil types (6.44 %); and IT5 as an exceptional oleoresin type (17.00 %, surpassing even Suranjana by 24.09 %). The near-independence of the three traits ($r \leq 0.25$) mandates trait-specific clonal selection. These accessions constitute validated quality donors for the turmeric improvement programme of the central Indian plateau and after multi-location stability testing, are candidates for varietal release for the quality-conscious domestic and export markets. Beyond varietal development, the results carry an immediate extension message: multiplication and promotion of the balanced-quality accession IT3 and the high-curcumin accessions IT1 and IT30 among the turmeric-growing tribal belts of Chhattisgarh can raise the intrinsic value of the state's produce in curcumin-linked markets without any additional input cost to farmers. The study also demonstrates the continuing value of indigenous germplasm as the primary reservoir of quality genes in this sterile triploid crop, and underlines the need to conserve, characterize and register such material before genetic erosion narrows the very diversity on which the turmeric quality industry depends.

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