REVIEW PAPER

From Field to Formulation: Agronomic Determinants of Curcuminoid Quality in Turmeric and Their Implications for Drug Delivery Systems

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ABSTRACT

Although curcumin, the primary curcuminoid found in turmeric (Curcuma longa L.), has been investigated for decades as a potential treatment, its quick metabolism, poor water solubility, and chemical instability limit its clinical application. A remarkable variety of carriers, such as liposomes, phytosomes, polymeric nanoparticles, micelles, and nanoemulsions, have been developed in response by delivery science. However, the majority of this research ignores the crop from which curcumin is derived and sees it as a fixed commodity. From the field to the formulation bench, turmeric is tracked in this review. We summarize the ways in which curcuminoid content, curcuminoid balance, co-occurring volatile oil, and contaminant load are influenced by genotype, soil and climate, light and water regime, nutrient management, harvest maturity, and post-harvest handling. We next go over why such variations are important for extraction, encapsulation, absorption, and delivery system repeatability. The evidence indicates that the main sources of variation in curcuminoid content are genotype and environment, that the effects of nutrients and biofertilizers on curcuminoid concentration depend on whether the nutrient was limiting, and that decisions about curing, drying, and extraction can significantly alter what ultimately reaches the formulator. A further twist is provided by human pharmacokinetic data: formulations can alter the plasma curcuminoid profile, allowing the curcuminoid ratio established in the field to reach the bloodstream. There are very few studies that directly relate agronomic factors to formulation performance We propose a minimum field-to-formulation data set that agronomists and formulation scientists can share, and we outline priorities for future work.

Keywords: turmeric; *Curcuma longa*; curcuminoids; agronomy; nutrient management; post-harvest processing; raw-material standardisation; bioavailability; nanocarriers

How to cite this article: Kamalakannan Sendilkumar, Praveena Katharine S, Suguna Devakumari M, Balaganesh Balashanmugavel, Suresh V, Lokeshwari M , R S Giriprasath ,"From Field to Formulation: Agronomic Determinants of Curcuminoid Quality in Turmeric and Their Implications for Drug Delivery Systems". Int J Drug Deliv Technol. How to cite this article: Sendilkumar K, Katharine PS, Devakumari SM, Balashanmugavel B, Suresh V, Lokeshwari M, Giriprasath RS., From Field to Formulation: Agronomic Determinants of Curcuminoid Quality in Turmeric and Their Implications for Drug Delivery Systems. Int J Drug Deliv Technol. 2026;16(88s): 1334-1344; DOI: 10.25258/ijddt.16.88s.127

1. INTRODUCTION

When you ask a formulation scientist where their curcumin came from, they will typically tell you the name of the source and the purity percentage. If you ask an agronomic the same topic, they will tell you about the monsoon, a district, a variety, and a planting date. Although the two professions hardly ever read each other's

publications, the two responses cover the same subject.

The pharmaceutical issue is real and well-known, so it is worthwhile to close that gap. Curcumin has been well evaluated for its potential in inflammatory, metabolic, neurological, and cancerous diseases, and it exhibits efficacy in a variety of preclinical models [1-3]. However, it dissolves poorly in water, breaks down in alkaline and light-exposed environments, and is quickly conjugated and excreted upon oral consumption [4,5]. Even high oral dosages result in extremely low quantities of the free compound in the blood [4,6,7]. The response from the pharmaceutical industry has been creative. To increase solubility, stability, and absorption, liposomes, polymeric nanoparticles, micelles, nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers, dendrimers, and phospholipid complexes have all been employed [8,9]. Highly bioavailable formulations are those that provide more than 100 times the absorption of unformulated curcumin, according to Stohs and colleagues' review. They also included a cautionary note: routine hydrolysis of plasma samples in pharmacokinetic studies has concealed the amount of free, active curcumin that actually reaches the blood [10].

Reading this literature as an agronomist is a curious experience. Almost every paper begins with "curcumin" as if it arrived in a clean vial. In reality, the starting material is a rhizome that grew in a particular soil, under a particular climate and nutrient regime, was harvested at a particular age, boiled or steamed, dried, ground and extracted. Each step leaves a signature. Curcumin content in turmeric collected across agro-climatic regions has been reported to range from 0.4% to 7.2% [11], a spread larger than many of the improvements that formulation papers are proud to claim. Commercial turmeric extracts also contain demethoxycurcumin and bisdemethoxycurcumin, along with volatile oil, oleoresin and sometimes unwanted contaminants [12]. If the input varies this much, it is fair to ask how much of the variation in formulation outcomes, and in the difficulty of reproducing them across laboratories, begins in the field.

This review tries to connect the two worlds. We first describe curcuminoid chemistry and biosynthesis (Section 2). We then examine the agronomic factors that influence curcuminoid content and quality: genotype, soil and climate, light and water, nutrient and biofertilizer management, harvest maturity and contaminants (Section 3). Post-harvest processing and extraction follow (Sections 4 and 5). Section 6 explains why these upstream variables matter for delivery systems, Section 7 proposes a field-to-formulation data framework, and Section 8 identifies gaps. This is a narrative review. It draws on peer-reviewed field, pot and laboratory studies, together with regulatory documents where these are the only available source, and we have tried to be open about where the evidence is thin.

2. CURCUMINOID CHEMISTRY AND BIOSYNTHESIS IN BRIEF

Curcuminoids are diarylheptanoids: two aromatic rings joined by a seven-carbon chain. Turmeric holds three of them, curcumin, demethoxycurcumin (DMC) and bisdemethoxycurcumin (BDMC), which differ in the number of methoxy groups on the rings [13,14]. Curcumin is usually the most abundant, but all three are present in the rhizome and in most commercial extracts, and they are not interchangeable. In side-by-side assays the three compounds, and the turmerones that travel with them, differ in how strongly they affect inflammatory and proliferative pathways [15]. The keto-enol character of the central chain explains much of the pharmaceutical behaviour of the whole family, including low solubility, metal chelation and susceptibility to degradation [5,13].

Inside the plant, curcuminoids come from the phenylpropanoid pathway. Phenylalanine is converted in several steps to feruloyl-CoA and p-coumaroyl-CoA. Two type III polyketide synthases then take over. Diketide-CoA synthase (DCS) condenses a hydroxycinnamoyl-CoA with malonyl-CoA to make a diketide intermediate, and curcumin synthase (CURS) joins that intermediate to a second hydroxycinnamoyl-CoA to complete the curcuminoid scaffold [16]. Which curcuminoid emerges depends on which CoA esters are combined.

Two details from the biochemical literature are worth keeping in mind. First, in enzyme assays curcuminoid synthase activity was detectable in several turmeric tissues and was highest in leaf extracts, while thioesterases that cleave phenylpropanoid CoA esters were abundant and may divert intermediates away from curcuminoid formation [17]. The rhizome stores curcuminoids, but it may not be the only place where they are made, and precursor supply competes with other fates. Second, turmeric carries several CURS genes, and cultivars differ in how DCS and the CURS isoforms are expressed, which is associated with differences in both total curcuminoid content and the balance among the three compounds [18].

These findings give a mechanistic reason to expect that anything altering carbon allocation, nitrogen status, light or stress in the crop could also alter curcuminoid output. They do not show that a given agronomic treatment does so in a field, and that distinction runs through the rest of this review.

Turmeric also makes more than curcuminoids. The rhizome contains volatile oil, in which ar-turmerone is a major constituent, and a mix of other phenolics and sesquiterpenoids, some of which are being explored as drug candidates in their own right [19–21]. Dried rhizomes typically contain a few percent of essential oil, and that oil does not contain curcuminoids [21,55]. For delivery scientists, this means that a "turmeric extract" can be a very different material depending on how the oil and curcuminoid fractions are handled, a point we return to in Sections 5 and 6.

3. AGRONOMIC DETERMINANTS OF CURCUMINOID CONTENT AND QUALITY

3.1 Genotype and genotype-by-environment interaction

If a grower wants to change curcuminoid content, cultivar

choice is the most dependable lever. Turmeric germplasm is genetically diverse, and collections from India and elsewhere show wide variation in rhizome yield, dry matter recovery and curcumin content [22]. What makes the story more useful for pharmaceutical supply is that genotypes differ in stability, not only in mean performance.

Aarthi and co-workers measured all three curcuminoids in 15 genotypes representing the main growing regions of India across three environments. IISR Prathibha recorded the highest curcumin content, statistically on par with SLP 389/1, IISR Pragati, Duggirala Red, Rajendra Sonia, BSR 2, CO 2 and Punjab Haldi 1. A stability analysis then showed that only some genotypes held their curcumin content steadily across sites: BSR 2, CO 2, IISR Prathibha and Duggirala Red [23]. A cultivar that is superb in one location and mediocre in another produces batch-to-batch variability that no downstream process can easily correct. For a pharmaceutical buyer, stable and high is worth more than very high and erratic.

The same study analysed the curcuminoids separately, not as one "total curcumin" figure [23]. That is still unusual in agronomic reports, and it matters for the delivery community because the ratio among the three curcuminoids is a property of both genotype and environment (Section 6.3).

3.2 Soil and climate

Environment shapes curcuminoid content strongly, although separating its strands is hard. Akbar and colleagues collected turmeric from different agro-climatic regions of India, recorded curcumin contents from 0.4% to 7.2%, and trained an artificial neural network on 11 soil and climate variables to predict curcumin content. Their sensitivity analysis pointed to minimum relative humidity, altitude, soil nitrogen and soil pH as the most influential inputs [11]. The model is correlative and built on a limited set of sites, so it should be read as a map of where to look and not as proof of causal control. Even so, it supports a point familiar to soil scientists: reaction and nitrogen status, not only fertiliser dose, belong in the quality discussion.

3.3 Light and water

Two physical stresses deserve attention because they can be managed by growers. Light has been studied in field plots under different shade levels and with exclusion of solar ultraviolet wavelengths. In that work, curcumin and DMC content were unaltered, while BDMC was higher under 50% shade than under UV exclusion. Because UV exclusion raised CO_2 assimilation and biomass, total curcuminoid yield per unit area was 21% higher than under the best standard shade treatment, and the authors concluded that selective wavelengths matter in turmeric cultivation [24]. In other words, the quality of light, not only its quantity, can influence which curcuminoids accumulate.

Water stress shows a different pattern. In a controlled experiment, withholding water for 21 days lowered net photosynthesis and chlorophyll but raised catalase activity and rhizome curcuminoid content; total curcuminoids rose by 106% over well-watered controls, although the increase in curcumin alone was not statistically significant [25]. Stress can concentrate secondary metabolites, but a stressed crop makes less rhizome, so an agronomist cannot treat drought as a quality tool. The finding is better read as evidence that curcuminoid accumulation responds to the plant's physiological state and not only to its nutrient supply.

3.4 Nutrient and biofertilizer management

Because turmeric is a nutrient-demanding crop, a large part of the agronomic literature is about fertiliser and manure. The most informative field study we found is a three-year trial at the ICAR-Indian Institute of Spices Research comparing organic, conventional and integrated nutrient management. Organic management combined farmyard manure, neem cake, vermicompost, ash and microbial inoculants. Conventional management used 60–50–120 kg ha^{-1} N–P–K as inorganic fertiliser. Integrated management combined half the nitrogen dose and the full P and K dose with organic manure and microbial inoculants. Integrated management gave the best soil quality, rhizome yield and uptake of N, P, K, Mg and Zn, followed by conventional and then organic management. Curcumin, oleoresin and volatile oil content, including the major oil constituents, did not differ significantly among the three systems [26]. The authors concluded that chemical nitrogen could be halved when combined with organic manure without penalising yield or soil quality.

Other studies report positive responses to individual inputs. In a pot experiment with factorial combinations of nitrogen and potassium, both nutrients raised rhizome yield and curcumin content, with the best performance at the higher doses [27]. Soil biology has also been studied: short-term addition of organic manures and biofertilizers altered biochemical and microbial characteristics of soils under turmeric [28]. And in a P-deficient soil with rock phosphate as the P source, a phosphate-solubilizing bacterium, *Bacillus safensis*, increased soil available P, rhizome yield and P uptake, and raised curcumin content by about 30–32.5% relative to the control, while allowing a 25% reduction in inorganic P [29].

These results look contradictory until we ask what was limiting. In a soil where nutrients were already adequate and the treatments differed mainly in source [26], curcuminoid concentration did not move. In a soil where phosphorus was clearly deficient [29], relieving the deficiency changed both yield and curcumin concentration. This reading is our interpretation, not a conclusion drawn by the original authors, and it needs testing in multi-site trials. But it fits what a soil scientist would expect and it suggests a practical message. Nutrient management is a strong lever on yield, uptake and soil quality and should be optimised. Its effect on curcuminoid concentration is likely to be largest when it corrects a real deficiency and small when it merely swaps one adequate source for another. Approaches that tailor doses to soil test values and target yields, combined with organic sources, fit this logic because they aim at efficiency and soil health without assuming that more fertiliser means more

curcumin.

3.5 Harvest maturity

Turmeric is a long-duration crop, and the day of harvest decides both what has accumulated in the rhizome and how it will behave in processing. In a comparison of two Punjab varieties harvested at an early stage and at full harvest, early-harvest rhizomes were irregular in growth, immature and poorer in nutritional and bioactive properties, and several physical and drying characteristics also differed [30]. The practical lesson is simple. Harvesting early to save time or catch a market window can lower the quality of the starting material in ways that later steps cannot repair. For pharmaceutical use, the harvest window should be treated as a specification, recorded in days after planting, and not left to convenience.

3.6 Contaminants: Soil, adulteration and the safety of the starting material

Curcumin itself has a favourable safety profile in most reviews [31], but a turmeric extract carries its contaminants with it. Regulatory reviews identify heavy metal contamination as a known safety issue for turmeric and curcumin products and describe two routes: cultivation on contaminated soil, and deliberate adulteration, for example with lead chromate, a yellow pigment used to brighten poor-quality rhizomes [32,51]. Turmeric powder can also be adulterated with powders of other *Curcuma* species, and regulators have examined cases of liver injury associated with turmeric supplements [33]. Lead-contaminated turmeric has been linked to product recalls in the United States and to very high lead levels in samples from rural Bangladesh [34,35].

For agronomists, the question is where the lead enters. A 2026 report by the advocacy organisation Toxics Link analysed 13 raw rhizome samples collected directly from farms in six Indian states. Lead ranged from below the limit of quantification (0.05 mg/kg) to 1.87 mg/kg, well under the Indian regulatory limit of 10 mg/kg, and the organisation concluded that contamination is more likely to occur after harvest, during processing, handling and storage, or through deliberate adulteration [36]. The sample is small and the report comes from an advocacy organisation and not from a peer-reviewed journal, so it should be read as indicative. A peer-reviewed survey of 356 turmeric samples from bazaars in 23 cities across India, Pakistan, Sri Lanka and Nepal found lead above 1000 µg/g in samples from Patna, Karachi and Peshawar, with lead-to-chromium molar ratios near 1:1 in the most contaminated samples, which points to lead chromate adulteration; polished roots were among the most affected forms [37]. The two findings are consistent: at least in the settings studied, the greatest risk lies downstream of the field. That does not remove the need to test soil and irrigation water, and the Toxics Link report itself recommends larger multi-state studies that include soil, irrigation water and agricultural inputs.

3.7 Summary of the evidence

Table 1. Agronomic factors and their reported influence on curcuminoid content and quality.

Factor	Main finding	Strength of evidence	Ref.
Genotype	Large differences in curcumin, DMC and BDMC; only some genotypes are stable across environments	Strong (multi-environment trial)	[23]
Soil and climate	Curcumin ranged from 0.4% to 7.2% across regions; humidity, altitude, soil N and pH most influential in a prediction model	Moderate (correlative model)	[11]
Light	Curcumin and DMC unaltered by shade or UV exclusion; BDMC higher under 50% shade than under UV exclusion; UV exclusion raised total curcuminoid yield by 21% through higher biomass	Limited (single study)	[24]
Water stress	Short drought raised total curcuminoids in rhizomes while lowering photosynthesis	Limited (controlled experiment, one variety)	[25]
Nutrient system	Integrated management improved yield, uptake and soil quality; curcumin,	Moderate (three-year field trial)	[26]

Factor	Main finding	Strength of evidence	Ref.
	oleoresin and volatile oil did not differ		
Individual nutrients (N, K)	Higher N and K raised yield and curcumin in pots	Limited (pot study)	[27]
Phosphate-solubilising bacteria	Raised yield and curcumin in a P-deficient soil	Moderate (greenhouse plus two-year field)	[29]
Harvest maturity	Early harvest gave immature rhizomes with poorer bioactive and physical properties	Limited to moderate (two varieties)	[30]
Contaminants	Soil contamination is possible; adulteration and post-harvest handling appear to be major sources of lead	Emerging	[32–37,51]

4. POST-HARVEST PROCESSING: CURING, DRYING AND STORAGE

After harvest, fresh rhizomes are normally cured by boiling or steaming, dried and often polished. Curing softens the tissue, speeds drying and fixes colour, but it also exposes curcuminoids to heat and moisture. Drying decides how long the material stays wet, how hot it gets and how much light it receives.

Kebede and colleagues studied three varieties, two curing methods (conventional and improved) and three drying methods (open-air, solar tunnel and greenhouse solar dryer) in a full factorial design. Moisture fell to roughly 6.4–7.7% under the best combinations. The highest curcumin retention, 6.99%, came from the variety Bonga 51/71 cured conventionally and dried in a solar tunnel dryer, whereas the highest oleoresin yield (13.88%) came from a different variety, Dame, cured by the improved method and dried in the open air. Open-air drying gave the lowest total and acid-insoluble ash, two pharmacognostic quality parameters [38]. The lesson is not that one protocol wins. Variety, curing and drying interact, and the protocol that maximises curcumin retention is not always the one that gives the cleanest or most oleoresin-rich material.

Temperature is the other half of the story. In a study of sliced rhizomes air-dried at 60 °C, with or without prior cooking at 95 °C, cooking itself had no impact on curcuminoid and essential oil content, while drying reduced curcuminoids by up to about 38% and essential oil by up to about 13%. Microscopy showed that the curcuminoids and the essential oil sit in different dedicated cells, and the authors suggested that the starchy matrix helps protect both during processing and recommended a short, gentle cooking step before drying to save time and energy [39]. This agrees with older work showing that heat processing can change the concentrations of bioactive principles in turmeric [40], and that fresh, dried and cured rhizomes differ in the composition of their volatile oil [41].

The chemistry explains why such care is needed. Curcumin is sensitive to light, heat, oxygen and pH, and its degradation produces compounds with their own biological activity [5,42,43]. That is a good reason to document drying temperature, duration and light exposure as part of the quality record. Material that was over-cooked or dried slowly under poor conditions may arrive at the extraction plant already carrying degradation products that influence downstream stability.

Table 2. Post-harvest steps and their relevance to delivery-grade material.

Step	What can change	Why it matters for formulation	Ref.
Curing (boiling/steaming)	Curcuminoid retention, drying time, texture, volatile oil composition	Starting concentration; degradation products	[38,39,41]
Drying (open-air, solar tunnel, hot air)	Final moisture, ash, curcuminoid and oil retention, colour	Moisture affects milling and extraction; ash profile signals cleanliness	[38,39]
Heat and light exposure	Curcumin degradation	Degradation products can affect stability and activity	[5,42,43]
Polishing and storage	Surface adulteration risk, moisture uptake	Contaminant load and microbial quality of extract	[32,36,37]

5. FROM RHIZOME TO EXTRACT

Extraction is the hinge between agriculture and pharmaceutics. Conventional solvent extraction is now supplemented by greener techniques, including supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE) and sequential schemes. Perez and colleagues extracted turmeric rhizomes grown in agroecological systems in Colombia by SFE followed by UAE. The SFE stage gave a lipophilic fraction rich in volatile compounds, with a maximum oil yield of 4.0%, and the UAE stage gave a more hydrophilic fraction rich in curcuminoids and phenolics. A nanoemulsion prepared from the extract showed no significant change after 15 days [44]. The study is useful because, within a single paper, it shows the whole chain from a defined agricultural source through fractionation to a delivery system, and because it shows that extraction can deliberately separate the volatile oil from the curcuminoids instead of leaving them as an accidental mixture.

The composition of any extract is also a function of the rhizome. Curcuminoid concentration, curcuminoid ratio, oleoresin and oil content all vary with genotype, environment and processing (Sections 3 and 4). An extraction process optimised on one batch may behave differently on another, and yields quoted per unit dry matter conceal moisture and ash differences that originate in curing and drying.

What is left after extraction is not necessarily waste. Spent turmeric is rich in starch and other biopolymers, and partial-hydrothermal hydrolysis of waste turmeric from supercritical and pressurised-fluid extraction has been shown to yield fermentable sugars and a starch-rich solid fraction with antioxidant constituents [45]. Whether such materials can serve as carriers or excipients is an open question, but it is one that agronomists and process engineers are better placed to ask together than apart.

6. WHY UPSTREAM VARIABILITY MATTERS FOR DRUG DELIVERY SYSTEMS

6.1 The delivery landscape in brief

Carriers developed for curcumin include liposomes, polymeric nanoparticles and micelles, nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers, dendrimers and phospholipid complexes [8,9,46]. Their shared aim is to improve solubility, protect the molecule from degradation and increase absorption or tissue exposure. In practice, a formulation is a matched set: a drug, lipids or polymers, surfactants and a process. When one element of the set changes unexpectedly, the whole behaves differently.

6.2 What human pharmacokinetic studies tell us about composition

Some of the strongest evidence that raw-material composition matters comes from human studies. In a randomised, double-blind crossover study, a lecithin formulation of a standardised curcuminoid mixture (Meriva) gave about 29-fold higher total curcuminoid absorption than the unformulated mixture. Intriguingly, the phospholipid formulation increased absorption of the demethoxylated curcuminoids much more than that of curcumin, so the main plasma curcuminoid after Meriva was DMC, not curcumin. Only phase 2 metabolites could be detected, and plasma concentrations remained lower than those needed to inhibit most anti-inflammatory targets in vitro [47]. A separate crossover study compared a phytosome formulation, a formulation with turmeric volatile oils and a formulation using a hydrophilic carrier with cellulose derivatives and antioxidants, and found large differences among them, with the hydrophilic carrier formulation absorbed 45.9-fold better than the standard curcuminoid mixture [48].

Two lessons follow. First, formulation can reshape the curcuminoid profile in blood, which means the ratio of curcumin to DMC and BDMC in the starting material is not a trivial detail. If a delivery system favours the demethoxylated compounds, the genotype and environment that set the ratio in the field [18,23] become part of the pharmacology. Second, absorption differences between products are often reported as large fold changes without full information about the botanical source of the curcuminoid mixture, which makes cross-study comparison difficult.

The piperine story is a good caution. A small pilot study with human volunteers reported a very large increase in curcumin bioavailability when piperine was co-administered [49]. But the UK Committee on Toxicity noted that this study included only eight participants, and that a later crossover study with 30 volunteers found no significant benefit of a piperine-curcuminoid combination over the standard extract [50,51]. Landmark claims in this field have sometimes rested on small samples, which is one more reason for formulation papers to document their materials carefully.

6.3 Raw-material attributes that can plausibly influence formulation outcomes

The following links are mostly inferential, because few studies have tested them directly, which is itself a main finding of this review.

1. **Curcuminoid purity and ratio.** Encapsulation efficiency, loading and release depend on the physicochemical behaviour of the encapsulated molecule. Because the three curcuminoids differ in substitution and polarity, a change in their ratio, driven by genotype or environment [18,23], could shift loading and release even when the label still says "curcumin". The human data above show that the ratio can also influence what appears in plasma [47].
2. **Co-extracted volatile oil and oleoresin.** In lipid-based systems the oil phase composition matters. Aromatic turmerone has been used to increase curcumin loading in microemulsions, on the reasoning that it mimics the natural co-occurrence of the two compounds in the rhizome

[52], and solid lipid nanoparticles co-loading curcumin and turmerone reached entrapment efficiencies of about 77% for curcumin and 75% for turmerone while reducing skin irritation relative to the free compounds [53]. An extract carrying variable amounts of turmeric oil will behave differently from a purified curcuminoid fraction, and sequential extraction offers a way to control this [44].

3. **Degradation products and moisture.** Over-processed material may contain degradation products [5,42,43], and residual moisture influences milling, flow and storage stability.
4. **Contaminants and adulterants.** Heavy metals and other adulterants are safety issues for any final product [32,33]. Concentration steps during extraction may raise them further, and nanoformulation does not remove them.
5. **Batch variability and reproducibility.** Pharmacokinetic comparisons between formulations are already difficult because of differences in dose, analytical methods and plasma sample handling [10]. Undocumented differences in the starting material add another layer of noise.

Table 3. Conceptual sensitivity of delivery platforms to raw-material attributes (hypothesis-generating, not experimentally established).

Platform	Raw-material attributes likely to matter most	Rationale
Nanoemulsions, microemulsions and self-emulsifying systems	Co-extracted oil content, curcuminoid ratio, degradation products	Oil phase composition and solubilisation capacity [44,52]
Liposomes and phospholipid complexes	Curcuminoid ratio and purity, oxidation-prone impurities	Ratio-dependent absorption shown for a phospholipid complex [47]
Solid lipid nanoparticles and nanostructured lipid carriers	Presence of turmerone or other lipophilic co-components	Co-loading changed entrapment and irritation [53]
Polymeric nanoparticles and micelles	Curcuminoid ratio, residual solvent and moisture	Loading and release depend on drug–polymer compatibility
Solid dispersions and cyclodextrin complexes	Purity, crystallinity, moisture	Dissolution and physical stability

7. TOWARD QUALITY STANDARDISATION AND A FIELD-TO-FORMULATION FRAMEWORK

Medicinal plant production already has a reference framework in the WHO guidelines on good agricultural and collection practices (GACP) [54]. These cover propagation material, cultivation, harvest, primary processing, storage and documentation, with the aim of consistent quality and safety. They are the natural starting point for pharmaceutical-grade turmeric. What is missing is a bridge between those records and the formulation literature, which currently begins at the extract.

We suggest that every study reporting a turmeric- or curcumin-based delivery system should state, at minimum, the information in Table 4. Much of it is cheap to collect, and agronomists are well placed to supply it.

Table 4. Proposed minimum field-to-formulation data set.

Stage	Information to record
Crop	Cultivar or accession, propagation material, location and altitude, season
Soil and climate	Soil pH, organic carbon, N, P, K and relevant micronutrients; rainfall and temperature summary; irrigation water source; light or shade conditions
Management	Nutrient sources and doses (organic, inorganic, integrated), biofertilizers, planting date, irrigation regime
Harvest	Days after planting at harvest, rhizome type (mother or finger)
Post-harvest	Curing method and duration, drying method, temperature, time and final moisture, storage conditions
Raw material quality	HPLC profile of all three curcuminoids, volatile oil, oleoresin, ash and acid-insoluble ash, heavy metals, microbial load, authenticity (absence of other *Curcuma* species)
Extraction	Method, solvent, conditions, yield, fraction composition
Formulation	Carrier, process, particle size, encapsulation efficiency, release and stability, analytical method

Stage	Information to record
	for each curcuminoid
Pharmacokinetics	Whether plasma samples were hydrolysed, and which analytes were measured

Figure 1 (to be prepared). Conceptual schematic of the field-to-formulation chain. Boxes for genotype, soil and climate, light and water, nutrient management, harvest and processing feed into the rhizome. Arrows then lead to extraction, to the extract (curcuminoids, volatile oil, contaminants) and to the delivery system and its pharmacokinetic profile. Feedback arrows show quality control data returning to the field.

8. RESEARCH GAPS AND FUTURE DIRECTIONS

Direct evidence is missing. We found no study that varies an agronomic factor in the field and then follows the harvested material through extraction and formulation to a measured delivery outcome. Designing such experiments, with replicated field plots, defined processing and a standard formulation platform, would be the most valuable contribution that agricultural and pharmaceutical scientists could make together.

Nutrient effects on quality need a deficiency-aware design. The apparent conflict between studies that find no effect of nutrient system on curcuminoid content [26] and studies that find large responses [27,29] may reflect differences in baseline soil fertility. Multi-site trials that report soil properties in detail, that include treatments both with and without a diagnosed deficiency, and that analyse the three curcuminoids separately would test this directly.

Genotype and stability. Multi-environment testing is already identifying genotypes that are high and stable for individual curcuminoids [23]. Extending this to volatile oil composition and contaminant uptake would give breeders targets that pharmaceutical users care about.

Physiological levers. Light quality and water status change curcuminoid accumulation in controlled studies [24,25], but their agronomic use has barely been explored. The trade-off between concentration and rhizome yield needs quantifying.

Predictive modelling. Prediction models based on soil and climate data [11] could be extended to harvest and processing variables, so that expected curcuminoid quality can be forecast before harvest.

Supply-chain safety. Current evidence suggests that heavy metal contamination of turmeric is, at least in part, a post-harvest and adulteration problem [36,37]. Traceability from farm to extract, backed by routine testing, is therefore as important as soil management.

Non-curcuminoid constituents. Turmeric oil and its constituents are attracting interest as drug candidates [19–21], and co-loading with curcumin has produced encouraging formulation results [52,53]. The agronomy of oil composition, which is much less studied than that of curcumin, deserves more attention.

Reporting standards. Journals can help by asking authors of formulation studies to document the botanical and chemical identity of their starting material in line with Table 4.

9. CONCLUSION

The journey of curcumin from a turmeric field to a drug delivery system is long, and most of its early stages are invisible in formulation papers. The evidence reviewed here indicates that genotype and environment largely set the curcuminoid content and balance of the rhizome, that nutrient management is best understood as a lever on yield, soil health and clean production whose effect on curcuminoid concentration depends on what was limiting, and that harvest maturity, curing, drying and extraction can each alter the material that finally enters a formulation. Human pharmacokinetic studies show that formulations can reshape the curcuminoid profile in blood, which gives the curcuminoid ratio set in the field a direct line to pharmacology. Contamination, whether from soil or adulteration, is a safety matter that no carrier can fix. None of this lessens the importance of carrier design. It does suggest that part of the bioavailability challenge, and part of the reproducibility challenge, can be addressed earlier in the chain. Closer collaboration between agronomists, post-harvest technologists and formulation scientists, supported by a shared minimum data set, is a practical place to start.

Declarations

Author contributions

Kamalakannan Sendilkumar: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Project administration. Praveena Katharine S: Supervision, Validation, Writing – review & editing. Suguna Devakumari M: Conceptualization, Supervision, Writing – review & editing. Balaganesh Balashanmugavel: Investigation, Resources, Data curation. Suresh V: Investigation, Resources, Validation. Lokeshwari M: Investigation, Formal analysis, Visualization. R S Giriprasath: Resources, Writing – review & editing. All authors read and approved the final manuscript.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-

profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics statement

Not applicable. This study did not involve human participants or animals.

REFERENCES

1. Prasad S, Aggarwal BB. Turmeric, the golden spice: from traditional medicine to modern medicine. In: Benzie IFF, Wachtel-Galor S, editors. Herbal Medicine: Biomolecular and Clinical Aspects. 2nd ed. Boca Raton (FL): CRC Press; 2011.
2. Hewlings SJ, Kalman DS. Curcumin: a review of its effects on human health. Foods. 2017;6(10):92.
3. Kunnumakkara AB, Bordoloi D, Padmavathi G, Monisha J, Roy NK, Prasad S, et al. Curcumin, the golden nutraceutical: multitargeting for multiple chronic diseases. Br J Pharmacol. 2017;174(11):1325–1348.
4. Anand P, Kunnumakkara AB, Newman RA, Aggarwal BB. Bioavailability of curcumin: problems and promises. Mol Pharm. 2007;4(6):807–818.
5. Nelson KM, Dahlin JL, Bisson J, Graham J, Pauli GF, Walters MA. The essential medicinal chemistry of curcumin. J Med Chem. 2017;60(5):1620–1637.
6. Gupta SC, Patchva S, Aggarwal BB. Therapeutic roles of curcumin: lessons learned from clinical trials. AAPS J. 2013;15(1):195–218.
7. Liu W, Zhai Y, Heng X, Che FY, Chen W, Sun D, et al. Oral bioavailability of curcumin: problems and advancements. J Drug Target. 2016;24(8):694–702.
8. Jacob S, Kather FS, Morsy MA, Boddu SHS, Attimarad M, Shah J, et al. Advances in nanocarrier systems for overcoming formulation challenges of curcumin: current insights. Nanomaterials. 2024;14(8):672. doi:10.3390/nano14080672
9. Yallapu MM, Jaggi M, Chauhan SC. Curcumin nanoformulations: a future nanomedicine for cancer. Drug Discov Today. 2012;17(1–2):71–80.
10. Stohs SJ, Chen O, Ray SD, Ji J, Bucci LR, Preuss HG. Highly bioavailable forms of curcumin and promising avenues for curcumin-based research and application: a review. Molecules. 2020;25(6):1397. doi:10.3390/molecules25061397
11. Akbar A, Kuanar A, Joshi RK, Sandeep IS, Mohanty S, Naik PK, et al. Development of prediction model and experimental validation in predicting the curcumin content of turmeric (*Curcuma longa* L.). Front Plant Sci. 2016;7:1507. doi:10.3389/fpls.2016.01507
12. Li S, Yuan W, Deng G, Wang P, Yang P, Aggarwal BB. Chemical composition and product quality control of turmeric (*Curcuma longa* L.). Pharm Crops. 2011;2:28–54.
13. Priyadarsini KI. The chemistry of curcumin: from extraction to therapeutic agent. Molecules. 2014;19(12):20091–20112.
14. Jayaprakasha GK, Jaganmohan Rao L, Sakariah KK. Chemistry and biological activities of *Curcuma longa*. Trends Food Sci Technol. 2005;16(12):533–548.
15. Sandur SK, Pandey MK, Sung B, Ahn KS, Murakami A, Sethi G, et al. Curcumin, demethoxycurcumin, bisdemethoxycurcumin, tetrahydrocurcumin and turmerones differentially regulate anti-inflammatory and anti-proliferative responses through a ROS-independent mechanism. Carcinogenesis. 2007;28(8):1765–1773.
16. Katsuyama Y, Kita T, Funa N, Horinouchi S. Curcuminoid biosynthesis by two type III polyketide synthases in the herb *Curcuma longa*. J Biol Chem. 2009;284(17):11160–11170.
17. Ramirez-Ahumada MC, Timmermann BN, Gang DR. Biosynthesis of curcuminoids and gingerols in turmeric (*Curcuma longa*) and ginger (*Zingiber officinale*): identification of curcuminoid synthase and hydroxycinnamoyl-CoA thioesterases. Phytochemistry. 2006;67(18):2201–2210.
18. Ayer DK, Modha K, Parekh V, Patel R, Vadodariya G, Ramtekey V, et al. Associating gene expressions with curcuminoid biosynthesis in turmeric. J Genet Eng Biotechnol. 2020;18:83. doi:10.1186/s43141-020-00101-2
19. Nair A, Amalraj A, Jacob J, Kunnumakkara AB, Gopi S. Non-curcuminoids from turmeric and their potential in cancer therapy and anticancer drug delivery formulations. Biomolecules. 2019;9(1):13.

20. Dosoky NS, Setzer WN. Chemical composition and biological activities of essential oils of *Curcuma* species. Nutrients. 2018;10(9):1196.

21. Orellana-Paucar AM. Turmeric essential oil constituents as potential drug candidates: a comprehensive overview of their individual bioactivities. Molecules. 2024;29(17):4210. doi:10.3390/molecules29174210

22. Sasikumar B. Genetic resources of *Curcuma*: diversity, characterization and utilization. Plant Genet Resour. 2005;3(2):230–251.

23. Aarthi S, Suresh J, Leela NK, Prasath D. Multi environment testing reveals genotype-environment interaction for curcuminoids in turmeric (*Curcuma longa* L.). Ind Crops Prod. 2020;145:112090. doi:10.1016/j.indcrop.2020.112090

24. Ferreira MI, Uliana MR, Costa SM, Magro M, Vianello F, Ming LC, et al. Exclusion of solar UV radiation increases the yield of curcuminoid in *Curcuma longa* L. Ind Crops Prod. 2016;89:188–194. doi:10.1016/j.indcrop.2016.05.009

25. Bharadwaj B, Sanathanam SK, Pham T, Cantrell CL, Wang M, Lee J, et al. Physiological and biochemical responses of turmeric (*Curcuma longa* L.) under drought stress. J Med Active Plants. 2024;13(2–3):40–55.

26. Srinivasan V, Thankamani CK, Dinesh R, Kandiannan K, Zachariah TJ, Leela NK, et al. Nutrient management systems in turmeric: effects on soil quality, rhizome yield and quality. Ind Crops Prod. 2016;85:241–250. doi:10.1016/j.indcrop.2016.03.027

27. Olaleye O, Fagbola O, Oduntan AO. Yield, curcumin and nutrient content of turmeric (*Curcuma longa* Linn.) in response to fertilizer application [Internet]. NIHORT HortBase; 2020 Oct 21 [cited 2026 Oct 7]. Available from: https://nihort.gov.ng/hortbase/yield-corcumin-and-nutrient-content-of-tumeric-curcuma-longa-linn-in-response-to-fertilizer-application/

28. Dinesh R, Srinivasan V, Hamza S, Manjusha A. Short-term incorporation of organic manures and biofertilizers influences biochemical and microbial characteristics of soils under an annual crop turmeric (*Curcuma longa* L.). Bioresour Technol. 2010;101(12):4697–4702.

29. Dinesh R, Srinivasan V, Praveena R, Subila KP, George P, Das A, et al. Exploring the potential of P solubilizing rhizobacteria for enhanced yield and quality in turmeric (*Curcuma longa* L.). Ind Crops Prod. 2022;189:115826.

30. Basha SJ, Kaur K, Kaur P, Singh TP. Effect of harvest stage on engineering, physio-chemical, bioactive and drying properties of turmeric. Technol Hortic. 2024;4:e022. doi:10.48130/tihort-0024-0019

31. Soleimani V, Sahebkar A, Hosseinzadeh H. Turmeric (*Curcuma longa*) and its major constituent (curcumin) as nontoxic and safe substances: review. Phytother Res. 2018;32(6):985–995.

32. Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT). Discussion paper on the potential risk to human health of turmeric and curcumin supplements – following an updated literature review (TOX/2022/35). London: Food Standards Agency; 2022.

33. Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT). Discussion paper on the potential risk to human health of turmeric and curcumin supplements following a recent product survey (TOX/2022/26). London: UK Food Standards Agency; 2022.

34. Cowell W, Ireland T, Vorhees D, Heiger-Bernays W. Ground turmeric as a source of lead exposure in the United States. Public Health Rep. 2017;132(3):289–293. doi:10.1177/0033354917700109

35. Forsyth JE, Nurunnahar S, Islam SS, Baker M, Yeasmin D, Islam MS, et al. Turmeric means "yellow" in Bengali: lead chromate pigments added to turmeric threaten public health across Bangladesh. Environ Res. 2019;179:108722.

36. Toxics Link. Lead in turmeric [report; press release dated 30 July 2026] [Internet]. New Delhi: Toxics Link; 2026 [cited 2026 Oct 7]. Available from: https://toxicslink.org/media/press-release/. Press coverage: Lead in turmeric? Not on farms, but during processing: study. Outlook India.

37. Forsyth JE, Mistree D, Nash E, Angrish M, Luby SP. Evidence of turmeric adulteration with lead chromate across South Asia. Sci Total Environ. 2024;949:175003. doi:10.1016/j.scitotenv.2024.175003

38. Kebede BH, Forsido SF, Tola YB, Astatkie T. Effects of variety and curing and drying methods on quality attributes of turmeric (*Curcuma domestica*) powder. Braz Arch Biol Technol. 2021;64:e21200697. doi:10.1590/1678-4324-2021200697

39. Yin M, Weil M, Avallone S, Lebrun M, Conejero G, In S, et al. Impact of cooking and drying operations on color, curcuminoids, and aroma of *Curcuma longa* L. J Food Process Preserv. 2022;46(5):e16643. doi:10.1111/jfpp.16643

40. Suresh D, Manjunatha H, Srinivasan K. Effect of heat processing of spices on the concentrations of their bioactive principles: turmeric (*Curcuma longa*), red pepper (*Capsicum annuum*) and black pepper (*Piper nigrum*). J Food Compos Anal.

2007;20(3–4):346–351.

41. Gounder DK, Lingamallu J. Comparison of chemical composition and antioxidant potential of volatile oil from fresh, dried and cured turmeric (*Curcuma longa*) rhizomes. Ind Crops Prod. 2012;38:124–131.

42. Schneider C, Gordon ON, Edwards RL, Luis PB. Degradation of curcumin: from mechanism to biological implications. J Agric Food Chem. 2015;63(35):7606–7614.

43. Kharat M, Du Z, Zhang G, McClements DJ. Physical and chemical stability of curcumin in aqueous solutions and emulsions: impact of pH, temperature, and molecular environment. J Agric Food Chem. 2017;65(8):1525–1532.

44. Perez A, Martinez-Correa HA, Parada-Alfonso F, Suárez Montenegro ZJ, Ballesteros-Vivas D, Álvarez-Rivera G, et al. Antioxidant, neuroprotective and anti-inflammatory activity of *Curcuma longa* extracts: from green extraction to nanoemulsion. Front Nutr. 2025;12:1619725. doi:10.3389/fnut.2025.1619725

45. Cárdenas-Toro FP, de Santana ÁL, Osorio-Tobón JF, Steel CJ, Meireles MAA. Partial-hydrothermal hydrolysis is an effective way to recover bioactives from turmeric wastes. Food Sci Technol (Campinas). 2018;38(2):280–292.

46. Ipar VS, Dsouza A, Devarajan PV. Enhancing curcumin bioavailability through nanoformulations. Eur J Drug Metab Pharmacokinet. 2019;44(4):459–480.

47. Cuomo J, Appendino G, Dern AS, Schneider E, McKinnon TP, Brown MJ, et al. Comparative absorption of a standardized curcuminoid mixture and its lecithin formulation. J Nat Prod. 2011;74(4):664–669.

48. Jäger R, Lowery RP, Calvanese AV, Joy JM, Purpura M, Wilson JM. Comparative absorption of curcumin formulations. Nutr J. 2014;13:11. doi:10.1186/1475-2891-13-11

49. Shoba G, Joy D, Joseph T, Majeed M, Rajendran R, Srinivas PS. Influence of piperine on the pharmacokinetics of curcumin in animals and human volunteers. Planta Med. 1998;64(4):353–356.

50. Fança-Berthon P, Tenon M, Bouter-Banon SL, Manfré A, Maudet C, Dion A, et al. Pharmacokinetics of a single dose of turmeric curcuminoids depends on formulation: results of a human crossover study. J Nutr. 2021;151(7):1802–1816.

51. Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT). Statement on the potential risk to human health of turmeric and curcumin supplements (COT/2024/07). London: Food Standards Agency; 2024. Available from: https://cot.food.gov.uk/node/13031

52. Aydin BS, Sağıroğlu AA, Bahadori F. Optimization and characterization of curcumin microemulsion formulations with aromatic turmerone-rich extract. Proceedings of the 8th World Congress on Recent Advances in Nanotechnology (RAN'23); 2023 Mar 23–25; Lisbon. doi:10.11159/nddte23.105

53. Aydin BS, Sagiroglu AA, Ozturk Civelek D, Gokce M, Bahadori F. Development of curcumin and turmerone loaded solid lipid nanoparticle for topical delivery: optimization, characterization and skin irritation evaluation with 3D tissue model. Int J Nanomedicine. 2024;19:1951–1966.

54. World Health Organization. WHO guidelines on good agricultural and collection practices (GACP) for medicinal plants. Geneva: WHO; 2003.

55. Machado Orellana MG, Orellana Paucar AM. Pharmacological profile, bioactivities, and safety of turmeric oil. Molecules. 2022;27(16):5055. doi:10.3390/molecules27165055