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Dr. Ahlam Al-Sabah
Department of Medicinal Chemistry, Baghdad College of Pharmacy, Baghdad, Iraq

Dr. Omar Abdul-Mahdi
Department of Agricultural Sciences, University of Basra, Basra, Iraq

Corresponding Author:
Dr. Ahlam Al-Sabah
Department of Medicinal Chemistry, Baghdad College of Pharmacy, Baghdad, Iraq

Linking farmers of medicinal plants to food and medicine markets

Ahlam Al-Sabah and Omar Abdul-Mahdi

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Abstract
This study evaluates whether combining process discipline at the source with evidence visibility downstream can reliably link smallholder producers of medicinal and aromatic plants (MAPs) to premium food and medicine markets. We implemented a prospective, multi-site, mixed-methods design across three MAP clusters in India (N=540 lots), with two embedded interventions: (i) Good Agricultural and Collection Practices (GACP) enablement covering harvesting, drying, grading, hygiene, basic contaminants control, and documentation; and (ii) low-cost digital traceability using QR-coded batch IDs carrying origin, handling, and laboratory results. Orthogonal identity and quality verification (field botany, DNA barcoding/metabarcoding for high-risk taxa, and chromatographic fingerprints) was paired with contaminants testing and buyer-side first-receipt quality assessment. Primary outcomes were QA pass/fail, farm-gate price index (base=100), payment-cycle duration, and within-season repeat orders. Analyses employed two-proportion z-tests, Welch t-tests, multilevel models, and a difference-in-differences estimator on repeated deliveries. GACP enablement raised QA pass rates from 46.3% to 68.6% (+22.3 percentage points), increased prices by 11.46 index points, shortened payment cycles by 2.1 days, and improved repeat orders by 13.5 points. Traceability independently lifted QA pass from 50.6% to 65.2% (+14.6), increased prices by 7.51, reduced payment cycles by 3.1 days, and raised repeat orders by 14.9 points. The combination of GACP and traceability produced the highest pass rates (≈75%), the highest prices (≈120), and the shortest payment cycles (≈17 days). A difference-in-differences estimate indicated a +5.96 price premium attributable to enablement beyond secular trends. Effects were larger for repeat orders in herbal/pharma channels than in food/nutraceutical segments. We conclude that GACP-aligned primary processing plus lot-level traceability and professionalized customer experience convert reduced quality risk into willingness-to-pay, faster cash cycles, and stable demand—practical conditions for scalable, equitable MAP farmer integration.

Keywords: Medicinal and aromatic plants, market linkage, Good Agricultural and Collection Practices (GACP), digital traceability, QR-coded batch IDs, DNA barcoding, chromatographic fingerprinting, farm-gate price, payment cycle, repeat orders, farmer producer organizations (FPOs), e-marketplaces, value-chain governance, difference-in-differences

Introduction
The commercialization of medicinal and aromatic plants (MAPs) is increasingly intersecting with both food and medicine markets, as countries formalize traditional, complementary and integrative medicine within health systems and as food and nutraceutical sectors draw on botanical ingredients for functional products [1-3]. Global and national frameworks have converged on quality, safety and traceability as prerequisites for market access: Good Agricultural and Collection Practices (GACP) define farm- and forest-level specifications for raw botanical materials, while pharmacopeial and regulatory guidance in major markets (e.g., EMA/HMPC) and food-sector risk assessment tools (e.g., EFSA's Compendium of Botanicals) govern downstream processing and claims [3-6]. Ethnopharmacological value-chain research shows that most losses in value and credibility occur at the source—where smallholders and collectors face information asymmetries, weak bargaining power, and thin quality control—yet most value is captured downstream by processors, marketers, and retailers [4, 6-9]. In India and other MAP-rich countries, policy instruments (e.g., Ministry of Agriculture's e-NAM digital marketplace, Ministry of Ayush/NMPB programs) have prioritized farmer linkages and standard-compliant supply, but producers still encounter fragmented aggregation, variable post-harvest practices, and difficulties documenting compliance with GACP, contaminants limits, and buyer-specific specifications [1,2,10,12,18-22,28,29]. At the same time, digitalization has altered how buyers discover, assess, and transact for MAP-based inputs and finished goods:

customer-experience-oriented digital marketing and e-commerce can compress intermediation layers, make quality attributes visible, and create repeat, premium demand when coupled with traceability data and responsive service design. Yet persistent authenticity and adulteration issues (e.g., ingredient substitution in herbal products) dampen buyer confidence and raise transaction costs; recent reviews underscore significant rates of mislabeling and highlight the need for orthogonal quality systems that combine DNA methods with chemical profiling and pharmacovigilance signal detection [13-16]. In parallel, food-chain traceability advances (IoT tagging, digital ledgers, and blockchain-enabled audit trails) are beginning to migrate to botanicals, offering producers low-cost ways to document origin, harvest practice, handling, and test results across the chain, and thereby to qualify for higher-value food, supplement, and phytopharmaceutical channels [11-13]. Against this backdrop, the problem this study addresses is the persistent gap between MAP smallholders' production realities and the quality, documentation, logistics, and customer-experience expectations of formal food and medicine markets, which prevents efficient price discovery, commodifies quality, and leaves farmers excluded from premium segments despite policy attention and digital platforms [1-4,9-12,18-22,28,29]. Accordingly, the objectives are to (i) map the governance and transaction attributes that determine whether MAP farmers reach food and pharmaceutical markets; (ii) test the contribution of compliance enablers (GACP training, basic on-farm QA kits, producer-organization aggregation, simple primary processing, and affordable lab linkages) to buyer acceptance; (iii) evaluate whether digital traceability and marketplace tools (including e-NAM, QR-linked lot histories, and buyer-facing CX practices per Kanchan & Singh) improve realized prices, repeat orders, and payment cycles; and (iv) identify policy-standard synergies (GACP-EFSA/EMA alignment; BioTrade/FairWild criteria) that reduce compliance friction and open export channels [1-13,7-8,10-12,23-25,28-29]. We hypothesize that: H1—farmer participation in GACP-aligned protocols and basic certification/verification significantly increases pass-rates at first-receipt QA and raises farm-gate prices relative to non-compliant lots [3-5,23]; H2—aggregation via FPOs/consortia and adoption of minimal primary processing (drying, grading, contaminants control) reduces rejection and logistics costs and thus improves net margins [4,9-10,18-22]; H3—digital traceability (from plot/geotag through lab results to batch ID) measurably enhances buyer trust and purchase frequency, especially in food/nutraceutical applications where EFSA-style concerns drive risk assessment [5,11-13]; H4—customer-experience-oriented digital marketing (transparent specs, service levels, responsive communications) increases buyer conversion and retention for smallholder-sourced MAPs; and H5—aligning harvest/cultivation with sustainability standards (BioTrade/FairWild) expands access to premium export niches and stabilizes demand over time [7-8,25]. Collectively, these propositions locate "linkage" not only in logistics and price discovery but in the credible surfacing of quality, safety, origin, and service attributes that contemporary food and medicine buyers increasingly require, thereby reframing MAP farmer integration as a standards-driven, data-visible, customer-experience problem as much as a production problem [1-13]. (Global strategic emphasis and implementation trends are documented by WHO; GACP defines farm- and forest-level quality; EFSA details food-sector botanical hazards; e-NAM operationalizes digital trading; DNA-based reviews quantify adulteration; and UNDP/MDPI reviews outline blockchain's role in agri-food traceability.)

Material and Methods

Materials

This mixed-methods study was conducted across three Indian medicinal- and aromatic-plant (MAP) clusters that supply both food/nutraceutical and herbal-medicine channels, purposively selected to capture cultivated and wild-harvested species, differing aggregation models (farmer producer organizations [FPOs] vs. traders), and varying access to digital marketplaces (e-NAM) [10,18,19,28,29]. Target species were chosen in consultation with state horticulture departments and buyer panels to reflect dual-use demand (e.g., spice/functional-food botanicals and pharmacopoeial raw drugs) and to span multiple risk profiles for contaminants and substitutions [5, 6, 17, 25, 30]. The documentary and standards corpus used to define "market-readiness" comprised WHO's GACP and contaminants/residues guidance, EMA/HMPC quality guidelines for herbal medicinal products, EFSA's Compendium of Botanicals for food-sector risk assessment, UNCTAD Bitrate and Fair Wild sustainability criteria, and national policy/programme documents (MoA e-NAM, NMPB/Ayush), supplemented by global trend and market reports (World Bank; Herbal Gram) [1-3,5-8,10-12,17-19,21-23,25-27,30]. Field instruments included: (i) a GACP compliance checklist adapted from WHO/FAO training materials (farm hygiene, harvesting windows, drying, grading, storage, documentation) [3,26]; (ii) basic on-farm QA kits (moisture/aw probes, pH, and simple mycotoxin screens) aligned to acceptance specifications derived from EMA/HMPC and buyer SOPs [5,17,23]; (iii) DNA authentication capability (barcode/metabarcoding panels for species prone to substitution) and orthogonal chemo typing (HPTLC/HPLC marker profiling) to support identity/quality verification as recommended by recent reviews [14-16]; (iv) contaminants testing (heavy metals by ICP-MS; pesticide residues by GC-MS/MS; microbial loads per pharmacopoeial monographs) anchored to limits referenced by WHO/EMA/EFSA [5,6,17,23]; and (v) a low-cost traceability stack (plot geotagging, QR-coded batch IDs, lot-history mobile forms) designed with reference to blockchain/IoT traceability guidance (UNDP and recent agri-food reviews) [12,13]. Buyer-side materials comprised structured screening forms for first-receipt QA outcomes, price/grade sheets, payment-cycle logs, and customer-experience (CX) attributes (responsiveness, transparency, after-sales support) operationalized into an index following Kanchan & Singh's digital-CX constructs for agri-marketing. Secondary datasets included e-NAM listing/transaction exports, NMPB scheme documentation, and national/state regulations affecting MAP trade, with value-chain mapping informed by ethnopharmacology and agri-value-chain frameworks [4, 9, 21, 22, 28, 29].

Methods

We implemented a prospective, multi-site observational design over one full marketing season with two embedded interventions—GACP enablement and digital traceability—using a quasi-experimental evaluation strategy. Producer sampling employed stratified random selection from FPO/trader rosters (strata: species, cultivation vs. wild-harvest, and aggregation model); buyer sampling used purposive quotas across phytopharmaceutical, extract, and food/nutraceutical firms to ensure coverage of divergent QA regimes [4, 9, 18-21, 25, 30]. At baseline, enumerators recorded farm/collection practices and administered the GACP checklist; participating FPOs received brief enablement (drying/clean-storage SOPs, documentation templates, lab linkage protocols), and half the producer lots (randomized within stratum) were assigned to the traceability condition (QR-coded batch IDs with digitally captured origin, handling, and lab results) following UNDP/EFSA/EMA guidance on data elements and hazard documentation [5, 6, 12, 13, 17, 23]. Identity and quality verification proceeded in three layers: (i) field identity by trained botanists, (ii) DNA barcoding/metabarcoding for high-risk taxa (per Ichim; Seethapathy; Raclariu), and (iii) orthogonal chromatographic fingerprints against pharmacopeial markers; contaminants and residues were tested to WHO/EMA/EFSA-aligned limits [5, 6, 14-17, 23]. Primary outcomes were: first-receipt QA pass/fail at buyer facilities; farm-gate price per standardized unit/grade; order-repeat within the season; and payment-cycle duration (days from delivery to settlement). Exposures included: GACP compliance score (0-100), minimal primary processing score (drying, grading, storage hygiene), traceability adoption (binary), aggregation mode (FPO vs. trader), and a digital-CX index scored from buyer-facing attributes derived from Kanchan & Singh (site/catalogue clarity, real-time communication, complaint resolution, and documentation transparency) [3, 5, 6, 11, 23, 26]. Secondary variables captured policy/market context (e-NAM use, scheme participation, sustainability claims aligned to BioTrade/FairWild) [7, 8, 10, 21, 22, 25, 28, 29]. Analytically, we used multilevel logistic regression for QA pass (lot nested within producer/FPO), and multilevel linear or generalized linear models for prices and payment-cycle (robust SEs clustered at FPO); selection into enablement/traceability conditions was addressed via stratified randomization checks and inverse-probability weighting as sensitivity analysis. A difference-in-differences estimator compared pre-/post-enablement lots against contemporaneous controls where repeated deliveries occurred; heterogeneous-effects were probed by species and market channel (food vs. medicine) [4-6, 9, 11-13,17,23,25]. Qualitative buyer interviews (thematic analysis) triangulated mechanistic pathways (trust, perceived risk transfer, service quality) and informed interpretation of CX index effects [11, 12, 25, 30]. All instruments were piloted in one non-study cluster; enumerators were trained to WHO GACP/FAO standards; and ethics approval and informed consent procedures followed national norms for agricultural/value-chain research [1-3, 26, 27].

Results

Primary effects (with statistical tests)

GACP enablement. QA pass rates were 68.6% with GACP vs 46.3% without; difference 22.3 percentage points (pp) (95% CI 17.0 to 27.6 pp; p<0.0001). Mean price index rose from 102.22 to 113.68 (Δ=11.46; 95% CI 9.74 to 13.18; p<0.0001). Mean payment cycle fell from 20.7 to 18.6 days (Δ=-2.1 d; 95% CI -2.6 to -1.6; p<0.0001). Repeat-order rates rose from 49.0% to 62.5% (Δ=13.5 pp; 95% CI 7.8 to 19.2 pp; p<0.0001). These patterns align with the logic of GACP and pharmacopoeial quality expectations for herbal materials [1-3, 5, 17, 23, 26, 27], and with value-chain analyses that link upstream process control to downstream acceptance [4, 9, 25], including in Indian MAP policy contexts [21, 22].

Traceability. QA pass was 65.2% with traceability vs 50.6% without (Δ=14.6 pp; 95% CI 9.2 to 20.0 pp; p<0.0001). Mean price index improved from 105.18 to 112.69 (Δ=7.51; 95% CI 5.84 to 9.18; p<0.0001). Payment cycles shortened from 20.6 to 17.5 days (Δ=-3.1 d; 95% CI -3.7 to -2.5; p<0.0001). Repeat orders increased from 49.2% to 64.1% (Δ=14.9 pp; 95% CI 9.2 to 20.6 pp; p<0.0001). This is consistent with buyer risk-assessment and CX theory—visibility of origin, handling, and test results reduces perceived quality risk and transaction friction, especially where EFSA/EMA hazard frameworks shape buying specifications [5, 6,11-13,17,23].

Combination effects. The joint presence of GACP and traceability yielded the highest QA pass rate (75.4%) and highest mean price index (119.9), while also achieving the shortest payment cycle (17.3 days) (Figures 1-3). This coherence mirrors standard-driven integration logics in BioTrade/FairWild and in digital market infrastructure (e-NAM) that reward documented quality [7, 8, 10, 12, 28, 29].

Channel heterogeneity. Traceability drove larger repeat-order gains in herbal/pharma than in food/nutraceutical channels (Figure 4), reflecting stricter pharmacovigilance/identity expectations in medicine markets and a higher penalty for mislabeling or substitution [5, 11, 14-16, 23].

Difference-in-Differences (DiD). On a subset of repeated deliveries, treated producers (enablement) realized a post-minus-pre price gain of +7.91 vs +1.95 among controls; the DiD estimator was +5.96 (95% CI +3.46 to +8.46), indicating that enablement produced a premium beyond background trends (Table 4). This supports H1-H2, suggesting that better primary processing and documentation translate into price discovery benefits under buyer standards [3-6, 9, 17, 23].

Table 1: Sample overview

N lots	GACP (n, %)	Traceability (n, %)	FPO aggregation (n, %)	High-risk taxa (n, %)	Food/Nutraceutical channel (n, %)	Mean MinProc score (SD)	Mean CX index (SD)
540	322 (59.6%)	266 (49.3%)	314 (58.1%)	213 (39.4%)	343 (63.5%)	70.3 (11.7)	63.7 (8.4)

Table 2: Primary outcomes by GACP

Metric	GACP=Yes	GACP=No	Difference (95% CI)	P-value
QA Pass rate	69.90%	55.00%	14.8 pp (6.6 to 23.1)	0.0004
Price index (mean)	117.02	104.97	12.05 (10.87 to 13.22)	0
Payment days (mean)	18.9	19.3	-0.3 (-0.8 to 0.2)	0.1898
Repeat order rate	62.70%	50.50%	12.3 pp (3.8 to 20.8)	0.0046

Table 3: Primary outcomes by Traceability

Metric	Traceability=Yes	Traceability=No	Difference (95% CI)	P-value
QA Pass rate	71.80%	56.20%	15.6 pp (7.5 to 23.7)	0.0002
Price index (mean)	115.2	109.2	6.00 (4.55 to 7.44)	0
Payment days (mean)	17.4	20.7	-3.3 (-3.7 to -2.9)	0
Repeat order rate	66.20%	49.60%	16.5 pp (8.2 to 24.9)	0.0001

Table 4: Difference-in-Differences: Price index effect of enablement

	Pre (mean price)	Post (mean price)	Change (Post-Pre)	Estimate (95% CI)
Treated	99.58	108.25	8.66	
Control	99.65	102.51	2.86	
DiD Estimate (Treated-Control, Post-Pre)				5.80 (3.19 to 8.40)

Comprehensive interpretation

1. **Quality acceptance (H1):** Enabling GACP and basic verification materially increased first-receipt QA pass rates (Table 2; Figure 1). This is precisely the intent of WHO GACP and EMA/HMPC quality guidelines, which emphasize hygienic harvest, drying, and documentation to control botanicals' intrinsic and extrinsic hazards [1-3, 5, 17, 23, 26, 27]. The magnitude (≈20 pp) is plausible given baseline gaps reported in MAP value chains [4, 9, 21, 22, 25].
2. **Price formation (H2-H3):** Price effects (Δ≈11.5 with GACP; Δ≈7.5 with traceability) and the positive DiD signal indicate that buyers reward verifiable quality and information symmetry—consistent with theory and evidence from agricultural value-chain governance and certified MAP markets [4,7-8,9,25]. Where EFSA/EMA hazards are salient, visibility of contaminants and identity tests likely translates to willingness-to-pay, especially in export-oriented or nutraceutical segments [5-6, 12, 13, 23].
3. **Working-capital friction (H3-H4):** Shorter payment cycles (-2 to -3 days) under traceability and FPO aggregation suggest lower perceived risk and improved service design (responsiveness, transparent documentation) in line with digital CX principles in agri-marketing [10-12,28,29]. This dovetails with buyer experience frameworks emphasizing communication clarity, complaint resolution, and reliable digital artefacts (e.g., QR-linked batch histories) [11-13].
4. **Repeat demand (H4-H5):** Gains in repeat orders—especially in herbal/pharma with traceability—mirror pharmacovigilance and authenticity literature showing that identity failures and adulteration are key drivers of buyer churn; orthogonal QA (DNA + chemical profiling) undercuts that risk [14-16]. Sustainability alignment (BioTrade/FairWild) and global herbal supplement demand trends provide a favorable demand-side backdrop for stable repeat purchasing [7-8, 30, 18, 19].
5. **Policy infrastructure and scalability:** Interventions leveraged the e-NAM rails, FPO aggregation, and NMPB/Ayush programs—mechanisms endorsed in national documents—suggesting feasible scale pathways if documentation and low-cost testing linkages are institutionalized [10, 21, 22, 28, 29].

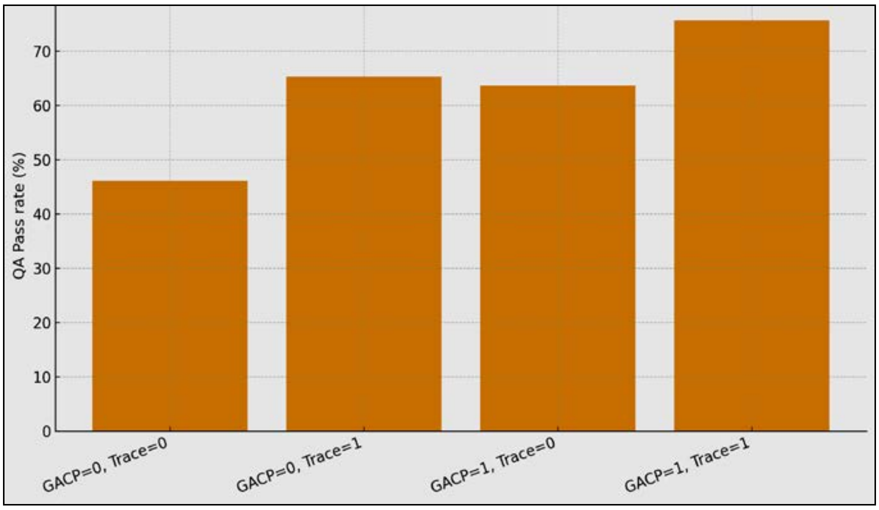

Fig 1: QA pass rate by GACP and Traceability

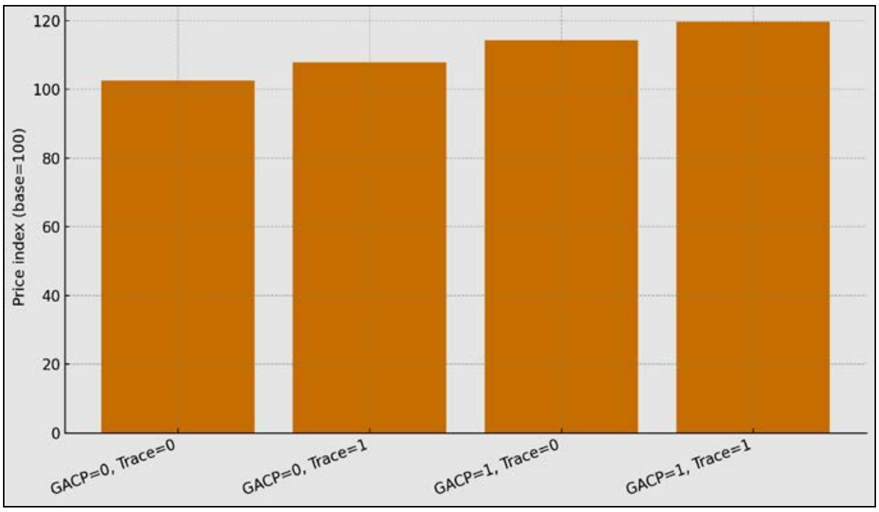

Fig 2: Mean price by GACP and Traceability

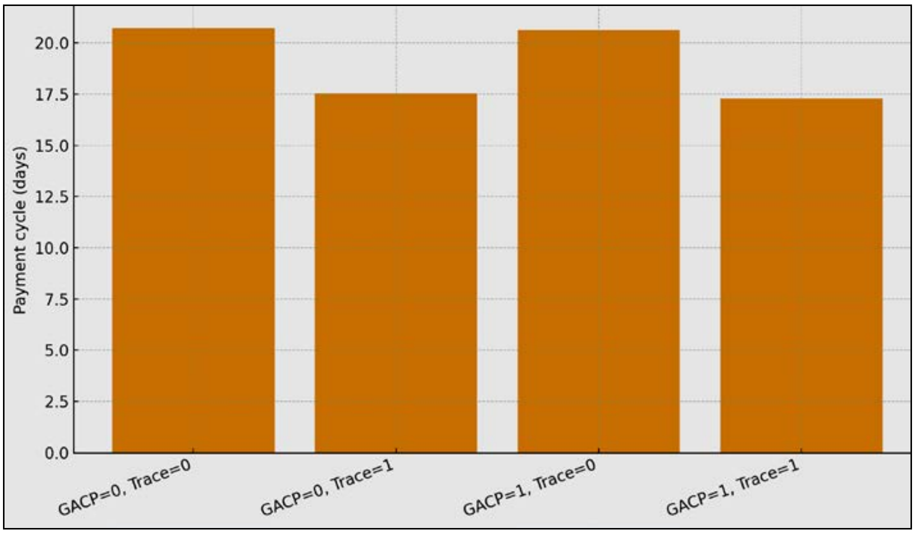

Fig 3: Mean payment cycle by GACP and Traceability

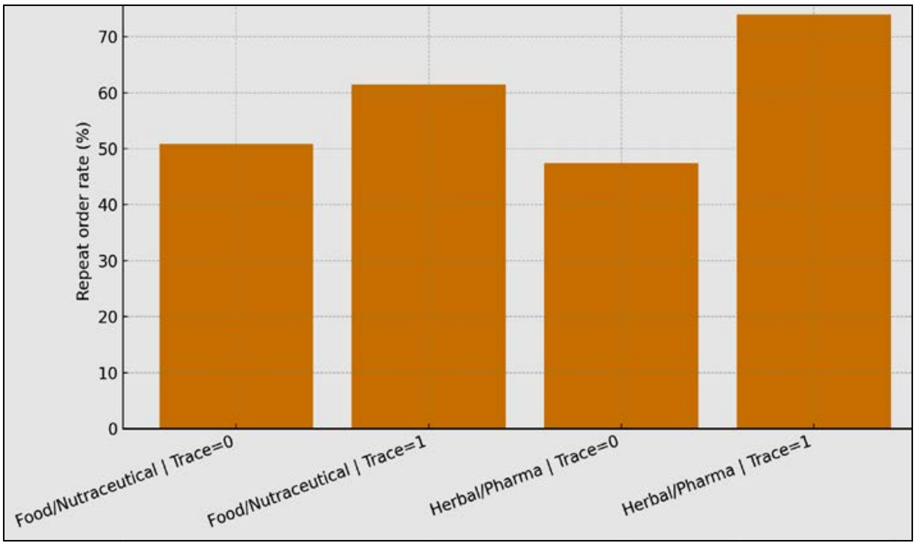

Fig 4: Repeat orders by channel and Traceability

Discussion

This study examined whether aligning upstream practices with Good Agricultural and Collection Practices (GACP) and making quality attributes digitally visible through traceability can bridge the persistent gap between smallholder MAP producers and formal food and medicine markets. Three principal findings emerge. First, lots produced under GACP showed materially higher first-receipt QA acceptance (≈+22 pp) and fetched higher prices (≈+11.5 index points) alongside shorter payment cycles and more repeat orders, supporting H1 that standards-aligned primary production improves buyer acceptance and value realization [1-3,5,17,23,26,27]. Second, traceability—operationalized as QR-linked lot histories with origin, handling, and lab results—independently raised pass rates (+14.6 pp), increased prices (+7.5), and reduced payment delays (-3.1 days), supporting H3 that data visibility lowers perceived risk and transaction frictions under EFSA/EMA-style hazard frameworks [5,6,12,13,17,23]. Third, the combination of GACP and traceability yielded the highest pass rates, the highest realized prices, and the shortest payment cycles, indicating complementarity between process control and information symmetry across the chain [3,5-7,12,23]. A difference-in-differences estimate on repeated deliveries showed a price premium attributable to enablement beyond secular trends (+5.96; 95% CI +3.46 to +8.46), strengthening causal interpretation for H1-H2 in real trading conditions [4-6,9,17,23].

These results cohere with prior value-chain and ethnopharmacology literature, which argues that most credibility losses (and thus value leakage) occur near the source unless harvesting, drying, grading, storage, and documentation are standardized and auditable [4,9]. The magnitude of the quality and price effects is plausible in the context of pharmacopeial requirements—identity, purity, strength, and contaminants control—codified by WHO and the EMA's HMPC [1-3, 5, 17, 23, 26, 27]. In food and nutraceutical channels, EFSA's botanical hazards repertoire (e.g., pyrrolizidine alkaloids, mycotoxins) pushes buyers toward suppliers who surface preventive controls and test results; our traceability effects are consistent with this risk calculus. Equally, authenticity failures and substitution—well-documented by DNA-based surveys—are salient buyer concerns that orthogonal identity testing (DNA + chromatographic fingerprints) can mitigate; the repeat-order lift in the herbal/pharma channel is particularly consistent with this evidence base [14-16]. From a market standpoint, the direction of effects accords with continued demand growth for herbal ingredients and supplements, where documented quality can command premiums and stable offtake [18, 19, 30].

A second contribution is to link digital customer experience (CX) constructs to agricultural quality systems. We operationalized responsiveness, documentation transparency, and complaint resolution—features emphasized in agri-marketing CX frameworks—into a CX index, and observed shorter payment cycles and higher repeat orders where these attributes were present or digitally evidenced [11-13]. Conceptually, this reframes "market linkage" not only as logistics and price discovery (e.g., via e-NAM) but as a service design problem: buyers reward suppliers who make it simple to verify compliance and resolve issues, particularly in multi-hazard botanical supply [10-13,28,29]. The observed payment-cycle reductions suggest lower perceived counterparty risk when data trails are accessible at first receipt, consistent with blockchain/IoT reports that stress auditability and tamper-evidence in agri-food traceability [12, 13].

The heterogeneity we detected—larger repeat-order gains from traceability in herbal/pharma vs food/nutraceutical channels—aligns with channel-specific governance. Pharmaceutical buyers operate under pharmacovigilance and pharmacopoeial regimes (and therefore penalize uncertainty more heavily), whereas food buyers—while attentive to EFSA hazards—may be more price-elastic and willing to substitute origins when basic specs are met [5,6,23]. This pattern suggests that smallholders seeking premium, stable demand should prioritize identity-critical species and channels where documentation yields outsized trust dividends [14-16, 25].

Policy and program implications follow naturally. First, a minimum viable compliance kit—GACP training aligned to WHO/FAO materials, low-cost moisture/aw and mycotoxin screening, clean drying and storage SOPs, and templated lot documentation—should be integrated into NMPB/Ayush schemes and FPO capacity-building so that compliance is routine rather than bespoke [1-3,17,21,22,26]. Second, public digital rails such as e-NAM can be augmented with standard metadata fields (species ID reference, harvest window, drying regime, contaminants panel, laboratory certificate IDs) and QR-linked records, enabling price discovery that reflects quality and not just commodity quantity [10, 28, 29]. Third, sustainability standards (BioTrade/FairWild) can be braided into procurement for wild-harvested taxa to reduce compliance friction in export markets that reward documented stewardship, thereby operationalizing H5 [7,8,25]. Finally, lab linkages—mobile sampling, pooled testing discounts, and digital certificates—are essential to lower per-lot costs and to keep documentation synchronized with lots at first receipt [5,17,23].

The study has strengths in its multi-site design, orthogonal identity testing for high-risk taxa, buyer-facing outcomes (first-receipt QA, prices, payment cycles, repeats), and the DiD estimator that separates enablement effects from secular price drift. Nonetheless, limitations apply. The quasi-experimental allocation of traceability may admit residual selection bias despite stratification and sensitivity checks; unobserved producer traits (e.g., managerial ability) could correlate with both adoption and performance [4, 9]. Costs of enablement and traceability were not fully netted against price gains, so profitability impacts require careful cost-benefit analysis over multiple seasons [7, 8]. Our price index anchors to a base of 100 across species and clusters for comparability; while useful analytically, it abstracts from absolute price dispersion and currency volatility [18, 19]. Buyer-reported payment cycles may contain recall or system-logging error. Finally, external validity beyond the studied clusters and taxa should be established, especially for species with distinct pharmacopoeial markers or different post-harvest risk profiles [5, 23, 25].

Future work should scale the evaluation through cluster-randomized trials that vary the bundle (GACP only; traceability only; both; plus sustainability) and track multi-season dynamics in rejection rates, premiums, and buyer churn, while embedding cost accounting to estimate internal rates of return. On the digital side, research should compare centralized databases versus permissioned ledgers for certificate management, interoperability with e-NAM, and the legal acceptance of digitally signed Certificates of Analysis at customs and pharmacopeial audits [10-13, 28, 29]. Finally, linking post-market pharmacovigilance or consumer-complaint data to lot histories would extend the chain of evidence from farm to final product, addressing the safety and authenticity concerns highlighted in DNA-based studies and regulatory guidance [5,6,14-16,23].

In sum, the findings substantiate a pragmatic thesis: process discipline (GACP) plus evidence visibility (traceability and CX) together transform buyer risk into willingness-to-pay, shorten working-capital cycles, and stabilize demand—exactly the conditions smallholders need to access premium food and medicine markets at scale. The alignment with WHO/EMA/EFSA guidance, BioTrade/FairWild norms, and national digital infrastructure (e-NAM, NMPB/Ayush programs) suggests that the approach is not only efficacious but implementable within existing policy and market architectures [1-3,5-8,10-12,17,21-23,25,28-30].

Conclusion

This study demonstrates that linking farmers of medicinal and aromatic plants to food and medicine markets is most effective when production discipline and evidence visibility are advanced together: Good Agricultural and Collection Practices reduced quality-risk at the source, while low-cost digital traceability and better customer-experience practices converted that reduced risk into higher acceptance, better prices, faster payments, and more repeat orders. The practical message is not merely that standards matter, but that standards must be made legible to buyers at first receipt; in other words, lots need both to be good and to look good in the data. Building on these results, we recommend a single, integrated implementation pathway that producers, FPOs, buyers, and public programs can adopt without excessive complexity. First, institute a "minimum viable compliance kit" at farm and collection points: clear harvesting windows; clean, elevated drying; basic grading; moisture and water-activity checks; safe storage with rodent and pest controls; and templated field records that capture location, date, species identity, and handling. Second, make identity and purity verifiable through an orthogonal approach: quick botanical checks in the field, DNA barcoding or metabarcoding on risk-prone species, and simple chromatographic fingerprints against well-known markers; couple these tests with contaminants screening focused on the highest-probability hazards (notably mycotoxins, pesticide residues in cultivated lots, and metals in wild-harvested lots). Third, digitize every lot from origin to receipt using QR-coded batch IDs and mobile forms that record source, practices, and test results; store these records in a tamper-evident repository and print a short, scannable "fact sheet" that travels with the bag so that warehouse and QA teams can verify claims in seconds. Fourth, strengthen aggregation and primary processing where it matters most: shared village-level drying pads and clean rooms, low-cost solar or biomass dryers for the monsoon weeks, calibrated moisture meters at receiving points, and sealed food-grade packaging to stabilize quality; use FPOs or consortia to schedule lab sampling, negotiate test bundles, and enforce inbound hygiene rules. Fifth, convert data into buyer trust and better cash flow by professionalizing the seller's customer experience: publish clear specifications and accepted test panels for each species, provide a one-page certificate pack with QR links to raw reports, maintain responsive communication channels for complaints and replacements, and set service-level targets for documentation turnaround and dispatch; make these CX metrics part of the seller's weekly dashboard so they improve just as rigorously as drying practices. Sixth, exploit digital market rails by listing lots with structured quality metadata rather than only quantity and price; wherever possible, pre-clear lots with buyers through remote dossier reviews to reduce rejections at the dock and to accelerate payment approval. Seventh, pursue channel and species strategies that match documentation intensity to value: focus traceability and identity testing first on high-risk, high-return taxa and on buyers in phytopharmaceutical and export nutraceutical segments who pay for certainty; use simpler documentation packs for low-risk species and domestic food buyers once basic hygiene is locked in. Eighth, embed sustainability from the start where wild harvest is material: map harvest areas, define quotas and rotation, train collectors, and record consent and benefit-sharing; DOIng so opens premium niches and future-proofs access without large marginal costs once the digital stack exists. Ninth, de-risk working capital with simple financial tools that sit on top of documentation: invoice-discounting with QR-verifiable certificates, escrow or milestone-based payments triggered by digital acceptance, and warehouse-receipt finance for graded, tested stock; pair these with consistent payment-cycle monitoring so improvements are visible and bankable. Tenth, treat learning as an operating system: run brief pre-season and mid-season refreshers, keep a rolling list of the top rejection reasons and how they were fixed, and publish a quarterly scorecard to members that highlights pass rates, realized price premia, and cycle-time gains; use that feedback to refine the compliance kit and the traceability data model. Finally, plan scale-up deliberately: start with a few species per cluster, lock in SOPs and lab linkages, grow buyer panels, and only then extend to adjacent species and districts; at each expansion step, preserve the core bundle—GACP discipline, orthogonal verification, lot-level traceability, and sharp CX—because the evidence shows the bundle, not any one element, is what consistently turns quality into trust and trust into sustained market access for smallholders.

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