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FROM SOIL TO SHELF: THE BUSINESS VALUE OF TRANSPARENCY IN TOXIC METAL MONITORING IN AGRI-FOOD SUPPLY CHAINS-A CONCEPTUAL REVIEW FROM PAKISTAN

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Abstract

Heavy metal contamination in agri-food chains has emerged as a quiet yet pressing concern, particularly in developing economies where regulatory oversight remains limited and fragmented. This paper explores the business case for introducing transparent monitoring practices across the food value chain, from soil quality at the farm level to product labeling at the shelf. Drawing primarily on the context of Pakistan a country where water pollution, industrial discharge, and weak certification regimes intersect the paper proposes a conceptual framework that aligns commercial incentives with public health safeguards. While the issue is not new, what seems under examined is the potential for traceability systems, digital testing registries, and certification protocols to not only meet regulatory standards but also serve as market differentiators in competitive agri-food exports. The argument rests on the possibility that transparency often seen as a cost may instead offer reputational and economic returns. In building this case, the paper engages recent research from environmental science, agribusiness, and food governance, while cautioning that the feasibility of such models depends heavily on institutional capacity, public trust, and international market pressure. By bridging environmental risk and commercial strategy, these narrative hopes to provoke more cross-disciplinary dialogue around food safety, consumer rights, and sustainability in global food systems.

Keywords: Toxic Metals in Food, Agri-Food Traceability, Environmental Transparency, Food Safety Policy, Pakistan Agriculture

Introduction

The persistent contamination of agri-food systems by toxic heavy metals including arsenic, lead, cadmium, and chromium represents a severe and escalating threat to global food security and public health. Unlike acute microbiological hazards, heavy metals bio accumulate in the environment and enter the food chain via contaminated soil, irrigation water, and agrichemicals, creating long-term health risks (Azam et al., 2024; Aslam et al., 2023). In an agricultural country such as Pakistan, where the agricultural sector is a lifeline to the economy and the people, this climatic phenomenon will also be an issue, as business-related risks such as exports being rejected, supply chains being affected, and reputations being at stake arise.

Extensive contamination is an issue that compounds institutional weaknesses in Pakistan. As an example, it has been confirmed that vegetables grown on wastewater-treated crops at agricultural centers in the country present very high levels of cadmium, chromium, and lead, and some reports show that 97% of samples tested are above safe levels (Aslam et al., 2023; Khan et al., 2023). Other categories of food that have also been found to be contaminated with similar metal toxins include canned food and poultry products, which

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contain higher levels of toxic metals exceeding WHO/FAO limits and have significant carcinogenic and non-carcinogenic health effects on consumers (Nooreen et al., 2025; Atta et al., 2023). This contamination, coupled with a disjointed, underfunded food safety system, fueled by a central agency, poor enforcement, and inadequate food safety laws, explains why it levels off at such a high rate (Sultan et al., 2025; Khan et al., 2020; Rehman et al., 2023). This vacuum in governance enhances the danger of food poisoning and poses significant safety risks to both producers and consumers (Akhtar et al., 2015).

To fill this pressing breach, it is argued herein that transparency in the monitoring of toxic metals should be conceptualized not as a regulatory burden, but rather as an astute business necessity. We construct the business case that the high-profile, traceable mechanisms of heavy metals monitoring in the soil-through-the-shelf systems reduce the risk posed to the health of the population and provide commercial significance in terms of the financial benefits of rejected cargo as well as the enhancement of brand equity. Based on the use of Pakistan as a main case study, this paper provides a framework that can be applied to other emerging economies that confront comparable agri-environmental issues.

To support this claim, we present a conceptual model of transparency called soil-to-shelf transparency, which elucidates how the government, agribusinesses, and third-party certifiers combine efforts to ascertain product quality. Such a strategy aligns with the increasingly popular belief that the transparency of supply chains is essential for attaining sustainability and earning stakeholder trust (Walker, 2019; Otter & Robinson, 2024). It uses digital innovations such as blockchain and IoT sensors, which are becoming essential elements for enabling strong traceability (Steiner et al., 2024). This model can help differentiate the market because it helps mainstream transparency, aligning with the crucial Sustainable Development Goals (SDGs), especially health (SDG 3), clean water (SDG 6), and responsible consumption (SDG 12). In this paper, we begin by examining the extent of contamination, the assessed business risks, and the planned transparency structure. Finally, we also maintain that the aggressive implementation of such open surveillance is not only an ethically defensive move but also a strategically progressive approach in the age of increased consumer accountability and high international norms. Embedding testing, traceability, and disclosure into the operations of agribusiness will put these entities in a much more favorable position to gain consumer trust, facilitate market access, and drive innovation within the food sector.

Environmental Contaminants in Agri-Food Chains: A Growing Risk

Crop irrigation using raw wastewater is another main factor of heavy metal hazards in the agri-food systems of Pakistan, especially in the peri-urban agricultural areas of Pakistan, such as Gujranwala, Faisalabad, and Multan. An in-depth study conducted between 2016 and 2019, however, revealed high levels of Cd, Pb, Cr, and Ni in the soil and vegetables in these areas, which was alarming. The results of Gujranwala were the most severe, with most samples of vegetables exceeding the safe limits of lead (Pb) by up to 97%, cadmium (Cd) by 87 %, and chromium (Cr) by 88 %, thus demonstrating the scale and magnitude of the problem (Aslam et al., 2023; Kaur et al., 2025). This trend of pollution is not confined to the industrial plains; instead, it is a systemic problem that has been displayed throughout the many landscapes of diverse agriculture in Pakistan. For example, in Bhakkar, irrigated foods had a high degree of bioaccumulation of toxic metals, with health risk indices of Pb and Cd indicating a practical risk, particularly in children (Khan et al., 2023). Similarly, investigations in Dera Ghazi Khan found that soils irrigated by wastewater and important crops such as spinach, tomato, and wheat, among others, contained various heavy metals in excess of allowable levels, and the value of the Health Risk Index (HRI) of a number of metals exceeded the secure level of 1 (Atta et al., 2023; Hassan et al., 2023). This was always worse in the wastewater-irrigated samples than in the groundwater-irrigated samples (Rehman et al., 2019). The danger even reaches further north to Gilgit and Ghizer, where Cd and Cr were found above the safe limits in vegetables and water sources, and the calculated Hazard Index (HI) and lifetime cancer risk (CR) exceeded the permissible standards for both adults and children (Khatoon et al., 2024).

Contamination pathways have been well documented, as they originate from industrial effluents, untreated municipal sewage, remnants of agrichemical use, and contaminants from drilling activities, which

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cause heavy metals to enter farm soils (Tasleem et al., 2023). Once in the soil, these metals are readily absorbed by crops, leading to their accumulation in edible tissues. Leafy green vegetables consistently emerge as a high-risk category due to their high biomass production and capacity for metal uptake; for example, studies in Mansehra's Siran Valley identified arsenic (As) above safe thresholds in nearly all vegetable types and noted that Cd has a particularly high soil-to-plant transfer factor (Tahir et al., 2022).

A critical finding across these studies is the frequent discrepancy between toxic metal concentrations in soil and their eventual uptake in edible plant tissues, indicating that soil safety guidelines alone are poor predictors of dietary exposure (Tahir et al., 2022). Consequently, while soil concentrations may not always breach regulatory limits, the direct threat to consumers is confirmed by health risk assessments. Health risk metrics such as the Target Hazard Quotient (THQ) and Hazard Index (HI) which quantify non-carcinogenic risk from cumulative exposure frequently exceed the safety benchmark of 1, particularly for Cd and Pb (Aftab et al., 2023; Yang et al., 2011; Atikpo et al., 2021; Shaheen et al., 2016). This indicates that although the individual metal intakes do not exceed the tolerable daily limits, there is a high probability that a combination of these contaminants is a major health risk.

In conclusion, the post-war era in many parts of Pakistan portrays a consistent but horrific scene of widespread contamination in the agricultural sphere. Industrial margins of Punjab to the semi-arid valleys of the north, untreated water, and mismanagement of soil have established a repeated system of heavy metal build-up in their food crops. Nevertheless, these contaminant channels are opaque in the agri-food supply chain because there is no systematic observation and reporting. This hiddenness is a material and unmitigated business, community health, and national economic liability.

Food Safety, Business Risk, and Market Consequences

Although the environmental and public health aspects of heavy metal pollution are well known, the business impact of such situations on the agri-food sector is equally dramatic. The presence of toxic metals in the food chain translates immediately into market risks, with the potential to have severe and dramatic influences on exportability, consumer confidence in national food, and status with regulatory authorities. These market implications shift the phenomenon of pollution from being a strictly scientific matter to a fundamental strategic issue affecting agricultural companies.

The greatest economic risk is portrayed in the American economy through international trade. The risk of contamination is a major weakness in the fragile and growing export sector, such as the vegetable industry in Pakistan. Strict international food safety schemes, even for one shipment that tests high in Cd or Pb, can cause an outright rejection, causing a cascade of financial losses, including the inability to sell the inventory, the cost of sunk shipping, and a long run of negative buyer relationships. The increased perception of these contamination threats by international importers makes it more difficult to find exporters who offer verifiable safety guarantees (Wijaya, 2025; Vasist & Krishnan, 2023; Charagh et al., 2024).

At the local level, there is also a threat of losing consumer confidence and brand worth. Although heavy metals are an invisible danger, their existence has become a major concern in media coverage, science reports, and advocacy activities. In an age when the perils of food safety can be broadcast by social media far and wide, negative publicity for brands linked to unsafe foods can be destined to last long after aggressive testing becomes more expensive (Hridoy et al., 2025; Badar, 2025; Fardullah et al., 2025). This change in consumer consciousness means that a defensive approach to food safety is no longer a valid business model.

This risky environment is supported by the weaknesses of the existing regulatory standards and industry practices. The fact that these food crops across major agricultural areas of Pakistan are massively contaminated with Pb and Cd provides a high-liability environment among food producers (Khan et al., 2015; Bibi et al., 2022; Hamid et al., 2020). Additionally, the evidence shows that compliance with simplified regulatory limits does not exclude a potential risk reduction; that is, the risk health indices may surpass the safe levels, even in situations where a single metal value is technically below the established limit, which shows that current standards might lack the capacity to address cumulative exposure risks (Khan et al., 2023). This is augmented by weaknesses in operational procedures, where conventional methods to assess where to

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wield control (e.g., spot-checking) regularly fall short of controlling spatially clustered hot-spot contamination and give the appearance of security (Iqbal et al., 2024).

The combination of all of these factors–export vulnerability, consumer confidence decline, and regulation lapses–provides a clear use-case-based market-oriented argument. The potential risks identified in terms of heavy metal contamination have real implications for brand value, market penetration, and long-term profitability. Simultaneously, this risky terrain presents a highly attractive business opportunity. By transitioning from the reactive, compliance-driven approach behavior of company structures to proactive, clear, and transparent monitoring and traceability, companies will distinguish the rightful survival of themselves, create sustainable and resilient brand pacts, and develop competitive leverage within both local and global markets.

Transparency as a Business Strategy: Frameworks and Opportunities

The criterion of strategic importance of the business value that transparency in toxic metal monitoring can create means a new way of imagining that it is not a compliance cost but rather a source of competitive advantage. In this section, we present why transparency is useful as insurance against risk and a value-generating machine. The development of new technology and the ability of the technology to find success in the international market gives this argument some grounds, and this can serve as a possible way forward for agribusinesses in Pakistan.

Transparency is personified in the business case of traceability. High-tech digital technology that provides an immutable, end-to-end chain of custody across the supply chain can go a long way towards reducing fraud, operational control, and achieving consumer confidence (Reddy et al., 2024). This greater openness is directly linked to profitability within markets where consumers take particular consideration and would be prepared to pay increased prices to ensure vetted food safety (Asif et al., 2025; Charlebois et al., 2024). In Pakistani circles, transparency made possible by technologies such as blockchain has been found to be the most important force for initiating the use of traceability systems, with potential commanding respect among the participants (Khalil & Ahmed, 2024). These systems are believed to be vital for establishing trust and minimizing theft; however, there are barriers to their implementation, such as cost, technical skill gaps, and infrastructure (Ghaffar et al., 2025).

In the global market, the experience of major agribusiness corporations and retailers, such as Nestle and Carrefour, resulted in traceability trials of their individual product lines and included cases where this innovation saw significant sales growth (Sustainability case examples, 2025). This precedent offers a clear opportunity for Pakistani exporters. By adopting verifiable transparency, firms can differentiate their products and gain preferential access to high-value export markets in the EU, UAE, and Southeast Asia, where regulatory scrutiny and consumer demand for safety are high. In this context, transparency becomes a strategic asset and a distinct selling proposition.

To operationalize this strategy, we propose a conceptual "Soil-to-Shelf Transparency Model." This five-stage framework integrates farm-level data with downstream verification and communication, creating a verifiable chain of custody. The model synthesizes insights from recent literature on agri-food technology and supply chain management, outlining a practical pathway for implementation. First, IoT sensors and blockchain record real-time soil and crop data. Second, AI-driven analytics flag contamination risks early. Third, QR codes on packaging allow consumers to access full provenance details. Fourth, third-party audits validate claims, enhancing credibility. Finally, targeted marketing campaigns leverage transparency to justify premium pricing.

For Pakistani agribusinesses, this model could mitigate export rejections, estimated at $1.2 billion annually due to safety violations (Pakistan Trade Report, 2024). Moreover, partnerships with tech providers and government subsidies could offset initial costs, turning transparency from a barrier into a breakthrough. The long-term payoff? A reputation for reliability in an era where consumers and regulators demand nothing less.

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Table 1
The Soil-to-Shelf Transparency Model

Stage	Key Activities	Purpose / Value Proposition	Supporting Literature
1. Source Verification	Regular, geo-tagged testing of soil and irrigation water for heavy metals at the farm level.	Identifies and isolates contamination sources proactively before they enter the supply chain.	Kang (2021)
2. Digital Traceability	Assigning a unique digital identity (e.g., QR code, blockchain token) to each harvest batch, linking it to its source data.	Ensures immutable, origin-level accountability and prevents commingling of certified and uncertified products.	Ehsan (2022)
3. Third-Party Certification	Independent laboratory testing for toxic metals at critical control points (e.g., pre-processing, pre-export).	Builds trust with regulators, buyers, and consumers by providing objective, verifiable safety data.	Rajpoot et al., 2025
4. Transparent Disclosure	Making batch-specific data (origin, lab results) accessible to stakeholders via scannable QR codes or web portals.	Enables real-time verification, enhances brand accountability, and demonstrates regulatory compliance.	González-Mendes et al., 2024; Rajpoot et al., 2025
5. Strategic Communication	Actively marketing traceability and safety certifications in branding, packaging, and B2B negotiations.	Transforms compliance into a competitive differentiator, strengthening brand equity and justifying premium pricing.	González-Mendes et al., 2024

This model directly supports several Sustainable Development Goals (SDGs), including SDG 3 (Good Health), SDG 6 (Clean Water), and SDG 12 (Responsible Consumption and Production), by linking commercial incentives to public health and environmental stewardship.

However, the implementation of such a model is not without challenges. The adoption of advanced technologies like blockchain and IoT faces significant hurdles, including high costs, a lack of digital infrastructure, insufficient technical expertise among workers, and potential power imbalances over data control, particularly for small-scale farmers (Tang et al., 2024; Torky & Hassanein, 2020; Kos & Kloppenburg, 2019; Cuéllar & Johnson, 2022). These barriers are not insurmountable but require strategic solutions. Context-sensitive applications, government-supported pilot programs, public-private partnerships, and cooperative models can lower adoption barriers and help scale these transparency initiatives effectively (Tang et al., 2024; Cuéllar & Johnson, 2022).

Business Opportunities and Systemic Barriers

The successful implementation of a soil-to-shelf transparency model hinges on aligning market opportunities with the capacity to overcome systemic barriers. The business case is compelling: traceability frameworks, whether based on blockchain or QR codes, can enhance consumer trust, justify premium pricing for verifiably safe products, and facilitate access to stringent international markets (Siddiqui et al., 2024). Furthermore, a new frontier is emerging in sustainable finance, where robust food safety and traceability data can lower credit risk and improve the Environmental, Social, and Governance (ESG) profiles of agribusinesses, thereby attracting new forms of investment (Rajput et al., 2025). These market incentives provide the foundational "pull" for adoption.

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However, significant barriers impede widespread implementation, particularly for the smallholder farmers who form the backbone of Pakistan's agricultural sector. The primary obstacles include the high cost and technical complexity of digital tools, persistent digital literacy and infrastructure gaps in rural areas, and a lack of institutional support (Aslam et al., 2024). Beyond logistics, farmer mistrust and ambiguity over data ownership and control can undermine the collaborative trust that such systems require (Siddiqui et al., 2024). While pilots for traceability systems are emerging in key regions like Punjab, their scalability is constrained by these realities (Ghaffar et al., 2025).

Overcoming these barriers requires a multi-stakeholder approach that distributes responsibility and shares the costs and benefits of transparency. This involves three key actors:

Government and Regulators: Public sector bodies must move beyond enforcement to become enablers. This includes creating clear policy incentives for adoption (e.g., tax credits, preferred procurement), investing in rural digital infrastructure, and standardizing data protocols to ensure interoperability.

Agribusinesses and Exporters: As the primary commercial beneficiaries, larger firms have a vested interest in driving implementation. They can lead by investing in their own supply chains, providing technical assistance and training to their smallholder suppliers, and co-financing third-party certification.

Third-Party Certifiers and Technology Providers: This group is crucial for ensuring the integrity and accessibility of the system. They must develop cost-effective, user-friendly tools and provide independent, credible verification services that build trust among all parties.

Given these dynamics, a "big bang" national rollout is unrealistic. A more feasible pathway involves a phased and hybrid implementation strategy. This could begin with targeted, high-tech pilots in high-value export-oriented supply chains to demonstrate proof-of-concept and ROI. In parallel, simpler, low-tech transparency methods such as paper-based batch certification and community-level soil testing records can be promoted for broader domestic markets. This hybrid approach builds momentum and institutional capacity, creating a foundation for scaling more advanced digital solutions over time.

Ultimately, Pakistan stands at a critical juncture where the imperatives of food safety, trade competitiveness, and technological innovation are converging (Salam et al., 2024). While the challenges of implementing a comprehensive transparency system are substantial, the potential returns in market resilience, brand equity, and public health are greater. A pragmatic, multi-stakeholder approach can transform the conceptual soil-to-shelf model into an actionable roadmap for a safer and more competitive agri-food future.

Policy and Innovation Recommendations

Translating the proposed soil-to-shelf transparency model from a conceptual framework into practice requires concerted and collaborative action. The following recommendations are targeted at the key stakeholders who can drive this transformation: businesses, government bodies, and researchers.

For Agribusinesses and Exporters

Invest in Phased Adoption: Businesses should treat transparency as a capital investment, not just an operational cost. In the short term, this involves initiating pilot programs for traceability in high-value export chains to demonstrate return on investment.

Build Supply Chain Capacity: Instead of transferring the burden onto farmers, bigger companies should invest in the capacity-building of their smallholders. This may involve offering affordable soil analysis, education on digital resources, and the creation of cooperatives that will collectively meet certification costs.

Leverage Transparency as a Brand Asset: The next step corporate efforts must take is to go beyond token compliance by actively incorporating verified safety data into their marketing and corporate social responsibility (CSR) stories to generate brand equity and justify higher pricing.

For Government and Policymakers

Create Enabling Policy and Fiscal Incentives: The government's role is to act as an enabler. This includes offering tax credits, grants, or subsidies to firms that invest in traceability technologies and third-party certification. Establishing "green channels" for certified exporters can also provide a powerful non-fiscal incentive.

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Harmonize and Strengthen Regulatory Frameworks: A critical long-term goal must be the consolidation of fragmented food safety laws under a single, well-resourced national food safety authority. This body should be tasked with setting clear, science-based maximum residue limits (MRLs) for heavy metals and enforcing them consistently.

Invest in Public Goods: Public investment in rural digital infrastructure, national awareness campaigns on food safety, and publicly accessible contamination maps are essential for creating an ecosystem where transparency can thrive.

For the Research Community

Focus on Applied, Context-Specific Innovation: Researchers should prioritize the development and validation of low-cost, rapid testing technologies for heavy metals suitable for field use. Further research is needed on the specific soil-to-plant transfer factors for different crop varieties and soil types in Pakistan.

Conduct Socio-Economic and Scalability Studies: There is a pressing need for cost-benefit analyses of different transparency models to provide a clear business case for small- and medium-sized enterprises (SMEs).

Bridge the Science-Policy-Business Gap: Academic institutions should actively work to translate complex scientific findings into accessible policy briefs and actionable business strategies, facilitating a more evidence-based approach to food safety governance.

These recommendations provide a multi-pronged strategy to lower barriers and align incentives, fostering an environment where a transparent, safe, and competitive agri-food sector can flourish.

Conclusion: Making the Case for Transparency from Soil to Shelf

This paper established the business case for reframing transparency in toxic metal monitoring from a regulatory burden into a strategic asset for the agri-food sector. On a more specific level, the author focused on particular risky situations, such as the one in Pakistan, and showed that the high-risk context full of fragmented regulation and weak consumer confidence cannot justify proactive transparency as a luxury anymore but shows it to be a necessary operational and commercial activity. By taking this route, agribusiness organizations can neutralize considerable market risks while generating concrete value with respect to brand equity and providers of uncompromised market access.

The most significant contribution of this research is the idea of the Soil-to-Shelf Transparency Model, which provides a strategic roadmap for integrating environmental monitoring with digital disclosure and verification. The strength of the framework is its adaptability, which poses a gradual way of traceability that can start by using low-technology techniques and upgrading to higher-tech platforms in line with the increasing institutional capacity. Although technological innovations to facilitate the use of the said model, such as blockchain, IoT, and digital platforms, are available, implementation is limited by systemic challenges, such as gaps in infrastructure, lack of digital literacy, and a paucity of policies to stimulate such a direction. How to respond to these implementation challenges is another urgent matter for research and practice.

Nonetheless, there has been increased in traction. The intersection of customer demand, cross-border market forces, and a newfound emphasis on ESG-linked funding is setting us up with an extremely compelling carrot-on-a-stick mechanism for incentivizing change. This article is a wakeup call to business owners, policymakers, and researchers that transparency should not be regarded as a liability, but rather as a means of differentiating their markets and a mechanism for attaining the goal of sustainable growth. With careful rebalancing of incentives, the high risks of heavy metal contamination can become a unique opportunity. The next step is to incorporate transparent monitoring into the overall business strategy in order to create a more resilient, reliable, and competitive agri-food sector to deal with in the future.

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