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Beyond The Source: Surge Capacity Failure and Cascading Risks in the Management of a Localized Radiological Emergency

Djarot Sulistio Wisnubroto¹, Suryantoro Suryantoro², Heru Prasetyo³, Dyah Sulistyani Rahayu⁴, Moch Romli⁵, Yarianto Sugeng Budi Susilo⁶, Roziq Himawan⁷, Purwantara Purwantara⁸, Parjono Parjono⁹, Ferly Hermana¹⁰, Totti Tjiptosumirat¹¹, Kristedjo Kurnianto¹², Budiyo Budiyo¹³, Irwan Santoso¹⁴, Baskan Hanurajie¹⁵, Jaja Sukmana¹⁶

Abstract

Localized technological emergencies can trigger cascading risks that overwhelm standard response protocols, yet evidence from resource-constrained urban settings remains sparse. This case study investigates the management of a localized radiological incident in a dense tropical neighborhood of Greater Jakarta, Indonesia, which unfolded under COVID-19 restrictions. The response stress-tested the national emergency management system, revealing a critical surge capacity failure: the generation of 906 drums of waste rapidly saturated the country's centralized predisposal infrastructure, forcing ad-hoc staging that compromised safety controls. Beyond logistics, the incident exposed cascading public health risks through often-overlooked ecological pathways, with Cs-137 activity in turmeric leaves reaching ~39,900 Bq/kg and leading to detectable internal contamination in residents. While excavation and capping reduced surface dose rates by >95%, this strategy transferred immediate risk into a long-term stewardship liability, creating new governance challenges. Our findings demonstrate how geographically confined incidents can expose profound systemic fragilities in urban disaster management. We conclude by proposing a resilient framework to guide future responses, focusing on decentralized surge-tolerant waste logistics, the explicit integration of ecological pathways into early warning systems, and performance-based triggers for long-term stewardship. These transferable lessons are crucial for moving from reactive emergency control to adaptive risk governance, particularly in resource-limited cities facing complex technological hazards.

Keywords: Disaster Risk Reduction, Surge Capacity, Cascading Risks, Emergency Management, Urban Resilience, Radiological Emergency, Waste Logistics, Tropical Cities.

¹ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310, Email: djar002@brin.go.id

² National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

³ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

⁴ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

⁵ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

⁶ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

⁷ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

⁸ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

⁹ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹⁰ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹¹ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹² National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹³ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹⁴ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹⁵ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310

¹⁶ National Research and Innovation Agency (BRIN), KST BJ Habibie, Tangerang Selatan, Banten, Indonesia, 15310



Introduction

Localized technological emergencies in dense urban environments often serve as stress-tests for a city's disaster risk reduction (DRR) systems. Such incidents can expose critical vulnerabilities in infrastructure, logistics, and governance, triggering cascading risks that extend far beyond the initial hazard. These systemic fragilities are particularly acute in resource-constrained, tropical cities, where rapid urbanization, institutional pressures, and climatic stressors converge. Understanding how these cascades unfold, from a primary event to failures in waste management, public health protection, and long-term risk governance, is essential for building urban resilience. However, empirical evidence from mid-scale emergencies in such contexts remains limited, leaving a gap in guiding effective preparedness and response.

Radiological incidents, though relatively rare, present a potent lens through which to study these systemic dynamics. The management of radioactive material demands rigorous protocols, yet it is precisely within these structured responses that underlying institutional and logistical weaknesses become most visible. In densely populated tropical cities, the challenges are distinct. High rainfall and fast ecological turnover alter environmental pathways; pervasive urban home-gardening creates short, localized food-chains; and public-safety decisions must be executed within tight logistical and institutional constraints. In tropical urban soils, radiocesium commonly concentrates in the upper 0–40 cm yet may remain detectable at depths to several tens of centimeters, and occasionally deeper depending on soil/hydrology where cores are available (Muto et al., 2019; Tatsuno et al., 2020); at the same time, several edible perennials typical of home gardens (e.g., turmeric, taro) have shown high activity concentrations, often exceeding 30,000 Bq/kg in leafy tissues, thereby shortening internal exposure pathways (Komatsu et al., 2021a; Takada et al., 2022b; Wen et al., 2025). Yet the peer-reviewed literature remains sparse on mid-scale events in resource-constrained tropical cities, where the problem is neither a catastrophic nuclear accident nor a small routine release, but something in between, urgent, complex, and highly contextual.

This article examines the localized Cs-137 contamination in the Batan Indah residential area (Greater Jakarta, Indonesia) as an evaluative case study in adaptive crisis management. The response unfolded under public pressure and COVID-19 social restrictions (Peleg et al., 2021), while relying on a highly centralized national waste infrastructure (PTLR–BATAN/BRIN) Serpong, ≈5 km from the site. Rather than recounting a chronology, we analyze the incident as a stress-test of policy and engineering choices: what worked, what broke, and what can be generalized (Linkov et al., 2022).

Terminology. In 2021, Indonesia consolidated several national research institutes, including BATAN, into the National Research and Innovation Agency (BRIN) (Burhani et al., 2021; Pemerintah Indonesia, 2021). Throughout this paper, “post-merger” refers to the period after that institutional integration, during which some operational archives were reorganized.

Building on recent syntheses of decontamination waste logistics, urban internal-dose pathways, and containment stewardship, mostly from temperate contexts but with limited coverage of tropical, resource-constrained cities, and situated within the DRR discourse on systemic vulnerability, we therefore ask: First, how resilient is a centralized waste architecture to a sudden, localized surge of contaminated materials, and what design features increase surge tolerance? Second, how material are internal exposure pathways through urban vegetation in a tropical context, and how should they reshape emergency communications and monitoring? Third, under what conditions is excavation–capping an acceptable containment strategy, and what long-term stewardship obligations follow in humid environments?

Contribution. Conceptually, we propose a practice-oriented analytical framework that evaluates response options along three dimensions: radiological safety, operational feasibility under constraints, and long-term sustainability/stewardship. This framework links engineering choices (e.g., centralized predisposal, soil-and-concrete capping) to systemic vulnerabilities with broader relevance (e.g., surge fragility in centralized systems, often-overlooked short food-chain pathways), specifying actionable policy levers pertinent for effective urban emergency environmental management, particularly demonstrated within resource-constrained, tropical urban settings (Mobbs et al., 2019). Methodologically, a key contribution of this study is to demonstrate how a robust and audit-ready technical analysis can be performed under common real-world constraints, such as the partial loss of archives and incomplete operational records following an incident. The paper thus offers a framework not only for radiological crisis management, but also for the reconstruction and evaluation of such crises when perfect operational data is unavailable, a widespread challenge in post-disaster incident review. Practically, the case provides empirical signals and transferable lessons to inform decentralized, surge-tolerant waste logistics, the integration of ecological pathways (like food chains) and mobile whole-body counting into early response assessment, and performance-based criteria for post-capping monitoring and stewardship triggers, elements crucial for improving urban emergency preparedness and long-term site management globally (Kinouchi et al., 2015; Takada et al., 2022b; Yamasaki and Utsunomiya, 2022). Throughout, we are explicit about emergency-driven limitations (restricted field replication; partial archival loss after institutional restructuring) and mitigate them via conservative parameterization, minimum documented QA/QC, pre-post verification, and controlled sensitivity analyses. (Mobbs et al., 2019; Taira et al., 2019).

2. Literature Review

This review is organized to surface three gaps that motivate the present case study: whether a highly centralized emergency-management architecture can absorb mid-scale waste surges in developing urban settings; how internal exposure via urban food-chain pathways should be treated in tropical ecosystems; and how decisions between containment and removal should be coupled to clear, long-term monitoring obligations (Bin Feng et al., 2022).

The challenges inherent in these gaps resonate strongly with core concepts in disaster risk reduction (DRR) and resilience engineering. The failure of a centralized system to absorb a sudden waste surge is a classic example of a lack of surge capacity, a critical component of resilient infrastructure (Linkov et al., 2022). The progression from the initial contamination event to challenges in waste logistics, then to public health impacts via food chains, and finally to long-term stewardship liabilities, exemplifies the phenomenon of cascading risks, where a primary incident triggers a chain of downstream failures across different systems (Pescaroli and Alexander, 2018). Furthermore, the choice between containment and removal is not merely a technical decision but a risk governance challenge, balancing immediate safety against long-term institutional capacity and financial responsibility. Viewing the Batan Indah incident through these theoretical lenses, surge capacity, cascading risks, and risk governance, allows for the extraction of transferable lessons that extend beyond the radiological context to other technological hazards in urban environments.

On waste logistics and system design, predisposal requirements emphasize graded, performance-based safety across characterization, treatment, and storage, with responsibilities distributed among operators and regulators; however, the standards do not prescribe centralization per se. In

practice, facilities sized for routine throughput are frequently stress-tested by episodic waste surges, producing ad-hoc staging and cross-traffic with baseline operations that can fragment safety controls (Arima et al., 2024; Théodon et al., 2024). This tension, routine sizing versus emergency peaks, underpins arguments for modular buffer capacity, emergency-only flow paths, and regional interim storage in geographically large or archipelagic nations, so that localized events do not overwhelm a single national node (Hirose and Povinec, 2022; Ivanov and Dolgui, 2021; Kundu et al., 2022).

A second body of work concerns internal exposure pathways. Radiocesium soil-to-plant transfer is highly site-specific, yielding heterogeneous uptake often elevated in leafy edibles (Sugiura et al., 2016; Takada et al., 2022c; Vanheukelom et al., 2025b). While the IAEA parameter handbooks remain the principal reference for transfer factors in dose assessments, most compilations and models derive from temperate settings. Evidence from humid tropical cities, characterized by high rainfall, rapid plant turnover, and pervasive home-gardening, indicates shorter, more local food-chain pathways and sub-parcel heterogeneity driven by patchy bioavailability and species-specific uptake (Taniguchi et al., 2019). In such contexts, individual monitoring (e.g., screening by whole-body counting (WBC) complements environmental surveys by verifying whether risk communications and temporary restrictions on garden produce actually reduce internal dose (Hosokawa et al., 2017; Tsubokura et al., 2015).

The third strand covers remediation strategy and stewardship. International guidance treats remediation as a stepwise process, problem framing, option screening, optimization, implementation, and long-term monitoring, with performance objectives defined up front (Chaloux-Clergue et al., 2024; Hashimoto et al., 2021; Onda et al., 2020). Where containment/capping is chosen over removal, best practice calls for documented as-built conditions, durable institutional controls, and explicit monitoring plans with triggers for corrective action if performance degrades, requirements that are especially salient in humid tropical settings where wet–dry cycling, micro-cracking, root intrusion, and shallow groundwater can erode barrier integrity over time (Shirai et al., 2023; Takada et al., 2022a; Vanheukelom et al., 2025a). Despite this, operational criteria for when to escalate from containment to renewed active remediation Comparative experience helps to bound expectations. Large-scale accidents such as Fukushima Daiichi generated extensive evidence on environmental transport, public dose, and long-term land recovery under nationwide mobilization (Taira et al., 2023), while the Goiânia accident remains the canonical urban Cs-137 case illustrating orphan-source forensics, urgent source recovery, intense public concern, and substantial waste-management challenges (Anjos et al., 2001; Obrador et al., 2022; Sakamoto-Hojo, 2018). These landmarks frame, but do not resolve, the distinct questions posed by mid-scale, localized incidents in densely populated tropical cities, where surge capacity, mixed-crew protection, ecological/internal pathways, and stewardship after containment must be delivered under tighter logistical and institutional constraints than in the better-documented high-income cases. To emphasize mechanisms rather than magnitude, Table 1 frames three reference contexts by problem class, system-stress relative to capacity, and the resulting transferable lessons.

Comparative framing (not a severity ranking). The table below juxtaposes three problem classes to surface mechanism-level lessons. It does not rank “size” or “severity”; instead, it contrasts system stress relative to available capacity and the type of constraints that shape transferable policy insights.

Insert Table 1 here.

In sum, the literature provides robust principles for protection, predisposal management, and

remediation, and well-developed radiocesium transfer models; what is comparatively scarce are evaluative case studies from tropical, resource-constrained urban settings that connect engineering choices to system performance under localized surges and overlapping crises. The present study positions the Batan Indah incident squarely in that gap, using conservative modeling, minimum documented QA/QC, pre–post verification, and sensitivity analysis to examine centralized bottlenecks, internal pathways, and performance-based stewardship in a real emergency context.

3. Methods

3.1 Study design and setting

We adopted an evaluative case-study design centered on the Batan Indah Cs-137 incident in a dense tropical urban neighborhood within Greater Jakarta. Because the work occurred under public scrutiny and COVID-19 restrictions, we used an emergency-adaptive approach: conservative parameterization to preserve safety margins (ALARA) (Kai et al., 2020b), minimum but documented QA/QC, and triangulation across sources (field measurements, operational records, regulatory verifications, and dose modeling). The aim was not exhaustive characterization but a defensible, audit-ready evidence base for analyzing policy–engineering trade-offs (Cardenas and Halman, 2016).

3.2 Data sources and provenance

Primary inputs consisted of: (i) the contemporaneous technical report of the remediation operation and (ii) the internal revised manuscript from the implementing agency. Following institutional merger and archival restructuring, some raw logs are no longer retrievable. We address this constraint explicitly by (a) pre–post comparisons at representative points (Teramage et al., 2016; Yasutaka and Naito, 2016), (b) sensitivity analyses around uncertain parameters (Pianosi et al., 2016; Saltelli et al., 2020), and (c) reconstruction of operational metrics (e.g., daily drum intake, dwell time in staging) from available manifests and transport schedules (Wilkinson et al., 2016; Zhang et al., 2019). All data used are reported in the Article and Supplementary Materials (S1–S4). Whole-body counting (WBC) results are de-identified at source.

3.3 Field, Laboratory, and Modeling

Procedures To support this analysis, we conducted environmental field sampling (dose-rate surveys, soil cores, vegetation, water), laboratory analysis (gamma spectrometry), and dose modeling (MicroShield 7.02) to evaluate remediation scenarios and verify engineering controls post-implementation. Detailed protocols for field mapping, sampling, laboratory analysis, specific QA/QC procedures, dose modeling parameters (including sensitivity tests), and pre-post verification data are provided in the Supplementary Materials ("Additional Methodological Details" section).

3.4 Personnel monitoring and protection

Personnel protection was adapted to the concurrent crises. Radiation and non-radiation staff were equipped with personal dosimetry (including EPDs where available) and informed by daily dose dashboards. Task design followed ALARA principles and was adapted to tropical heat/humidity through scheduled hydration, micro-breaks, and portable ventilation (Hamd et al., 2025; Khorshid and Song, 2025; Koch et al., 2024).

3.5 Operational metrics reconstruction

To quantify the waste-handling bottleneck, we reconstructed daily drums received/processed and estimated staging dwell time from manifests, transport logs, and work schedules. We summarize these metrics in Supplement S4 and use them to compute the ratio of peak load to effective

throughput, which underpins the analysis in Section 4.1 on surge capacity (Caldera et al., 2025a).

3.6 Ethics and Data Governance

WBC measurements were conducted as part of emergency public-health services; data are anonymized and reported in aggregate (Cho et al., 2018). All field operations and waste transfers followed applicable licenses and regulatory oversight. This approach aligns with the study's purpose: decision support under constraint (Glavič-Cindro et al., 2020; Hoti et al., 2021).

4. Results and Discussion

4.1 A Surge Capacity Failure: Stress-Testing the Centralized Waste Infrastructure

The Batan Indah remediation generated a waste surge that exposed the quantifiable fragility of Indonesia's single-node predisposal architecture, forcing ad-hoc operational responses that compromised standard safety protocols. In total, 906 drums (487×100 L steel and 375×150 L HDPE of contaminated soil; 25×150 L HDPE of vegetation; 19×100 L steel of used PPE) were routed to PTLR–BATAN Serpong (≈ 5 km). Available staging space was exceeded; overflow occupied the Pre-treatment Room IS-1 (Building 52) and the access corridor of the Decontamination Installation (Building 53), restricting equipment maneuverability and complicating radiological oversight (see Figure 1 for site context). Table 2 consolidates the waste inventory and staging path, while Figure 2 depicts its composition and flow.

Insert Figure 1 here.

Analytically, the episode exposes a structural vulnerability intrinsic to a highly centralized waste architecture calibrated for routine throughput rather than emergency peaks. This is a case of single-node fragility: when a sole national predisposal node must absorb both routine and surge flows, the safety chain, from packaging and labeling through transfer and exposure monitoring, begins to fragment under sudden, localized loads (Caldera et al., 2025; Chen et al., 2021; Zahiri and Suresh, 2021). PTLR's rapid construction of a semi-permanent transit shelter adjacent to Interim Storage-2 mitigated the immediate overflow and enabled continued receipt of drums, with compaction adopted as the first treatment step to reduce volume (Yamasaki et al., 2022).

Operational triage. Once the transit shelter was available, **dose-based staging** was implemented: drums with **dose rates** $\leq 10 \mu\text{Sv}\cdot\text{h}^{-1}$ were routed to the shelter for temporary holding, while $> \sim 10 \mu\text{Sv}\cdot\text{h}^{-1}$ remained at **IS-1** for pre-treatment/compaction, reducing corridor dwell times and easing radiological oversight (measurement geometry specified in **Supplement S1**). Yet compaction alone is an interim measure; longer-term stability of Cs-137–contaminated soils in a hot–humid climate typically requires immobilization/encapsulation to control remobilization risk and to simplify subsequent handling in alignment with ALARA (Chindaprasirt et al., 2023; Jain et al., 2025).

The “proximity dividend” in this case is non-generalizable across an archipelagic nation: similar incidents in remote provinces would confront road constraints, weather, and limited licensed carriers, amplifying environmental and public-health risk if staging areas are not engineered for prolonged waits. Policy-wise, the case argues for a more distributed, surge-tolerant architecture: licensed regional interim stores capable of receiving overflow, complemented by mobile units for on-site compaction, characterization, and packaging (Hasani Goodarzi et al., 2024; Zhang et al., 2024). National facilities should incorporate modular buffer bays, emergency-only material routes, and dedicated transfer equipment to avoid cross-traffic with routine operations. Standardized drum/liner/pallet specs and barcode/RFID tracking would streamline inventory control, daily inspection, and auditable radiation safety, while performance-based criteria should govern escalation from compaction to immobilization to avoid technical debt later in the cycle

(Pratap et al., 2024; Razak et al., 2023).

Quantifying the surge (range). Over a plausible 3–6-week window for excavation, packing, and transfer, the operation generated **906 drums**, i.e., **151–302 drums·week⁻¹**. Relative to a routine predisposal throughput **R (drums·week⁻¹)**, the surge intensity is **$I = (906/T)/R$** , yielding **$I \approx (151–302)/R$** . Even at the upper bound of **R**, the overflow into corridors and emergency sheltering indicates **quantifiable single-node fragility**, not merely anecdotal congestion.

Overall, the incident demonstrates that a pure centralization model is fragile under peak loads even for geographically small events. A calibrated hub-and-spoke network, with the national center as the terminal node, not the only node, offers faster, safer, and more resilient waste logistics in a large island nation (Hasani Goodarzi et al., 2024; Zahiri and Suresh, 2021).

Insert Table 2 here.

Insert Figure 2 here.

4.2 Adaptive Crew Management: Protecting a Mixed Workforce Under Concurrent Crises

Policy implications up front. This pattern reveals a critical gap in standard emergency protocols: **radiation-protection models designed for trained radiation workers are inadequate for managing the sporadic, high-gradient tasks assigned to mixed, non-specialist crews in dynamic urban incidents.** Consequently, pre-task briefings anchored to hotspot maps, **real-time alarmed dosimetry, temporary shielding at repetitive work points, and same-day rotation redesign** should be treated as baseline controls, not optional enhancements.

The multi-agency workforce exhibited distinct exposure profiles between radiation workers and non-radiation staff. Personal dosimetry showed that among radiation workers, the highest daily dose reached 87 μSv , with a weekly cumulative of 142 μSv ; among non-radiation staff, the highest daily dose reached 7 μSv with a weekly cumulative of ≈ 15 μSv . Although safely below annual regulatory limits, the daily traces reveal task-linked spikes, particularly when non-radiation personnel made brief entries into controlled zones (Sailer et al., 2017; Vano et al., 2023; Wilson-Stewart et al., 2023). The pattern indicates that rotation and time-at-risk controls were effective for weekly totals, yet peak daily excursions can still occur when task geometry or routes traverse local gradients (see Table 3 for a summary) (Sailer et al., 2017; Vano et al., 2023).

In practice, ALARA was achieved through duration limits, distance optimization, and opportunistic shielding; however, the uneven spike profile among non-radiation staff points to a need for more conservative task engineering (López et al., 2018; Sailer et al., 2017). Brief, data-driven pre-task briefings, using updated hotspot maps, designated ingress/egress routes, and target dwell times, combined with temporary shielding at repetitive work points help flatten daily peaks without sacrificing pace (Da Silva et al., 2018; Khan and Yi, 2024). Electronic personal dosimeters (audible/visual/vibration alarms) supported timely exits, while a daily dose dashboard at the field post enabled same-day rotation redesign (see Supplement S4 for the template) (Loose et al., 2024; Vano et al., 2023).

Tropical heat and humidity added thermophysiological strain that can silently lengthen dwell time; scheduled hydration, micro-breaks, and portable ventilation helped maintain work tempo without eroding protection margins (Alahmad et al., 2024; Hansson et al., 2024; Morris et al., 2020). Clear zone markings, one-way logistics in narrow corridors used for drum movement, and shielded waiting points further reduced avoidable proximity (Da Silva et al., 2018; Sailer et al., 2017). Executed under COVID-19 social restrictions (PSBB) that constrained crew sizes and sequencing, this overlapping-crisis context validates an adaptive, data-driven approach rather

Insert Table 3 here.

4.3 The Overlooked Vulnerability: Cascading Public Health Risks from Tropical Food Chains

Our findings reveal that short, efficient food-chain pathways are a dominant and frequently underestimated risk vector in tropical urban ecosystems, shifting the critical locus of exposure from external surface dose to internal dose via home gardening. Environmental measurements indicate that household vegetation constituted a salient internal exposure pathway (see Table 4; Figure 3). Turmeric leaves from affected yards reached $\sim 39,867$ Bq/kg of Cs-137, while several other edibles (e.g., citrus, soursop, grasses) also showed notable activities. By contrast, water samples were much lower (~ 0.11 Bq/L), indicating that drinking water was not the dominant route in the post-incident phase (Merz et al., 2015a; Nakanishi and Sakuma, 2019). Consistent with tropical urban soils, radiocesium concentrated in the upper 0–40 cm and remained detectable at depth where cores were available (Imamura et al., 2017; Takahashi et al., 2015), creating heterogeneous “bioavailability patches” at sub-parcel scales that can drive species-specific uptake (Komatsu et al., 2021b; Velasco and Anjos, 2021a). In parallel, whole-body counting (WBC) of 13 residents identified four with detectable Cs-137 body burdens; interviews linked all four cases to consumption of produce harvested within the contaminated zone (Orita et al., 2016). Follow-up measurements four months later showed declines to at/below detection in three and below threshold in one, consistent with cessation of intake and biological elimination, with the highest estimated committed effective dose of 0.12 mSv (see Supplement S3) (Yoshida-Ohuchi and Shinohara, 2020).

Analytically, these findings caution against response designs that over-weight surface dose mapping while under-weighting ecological pathways. In tropical cities, with high rainfall, rapid plant turnover, and widespread home-gardening, bioavailability can vary over meters, and crude zonation may miss high-uptake species or micro-hotspots. Accordingly, emergency communications should include temporary advisories against consuming high-uptake leafy herbs from the zone of concern, coupled with targeted WBC screening for residents known to consume home produce (Li et al., 2022; Orita et al., 2016). Regional or mobile WBC capacity would extend access beyond referral-based systems and allow earlier identification of cases. Framing vegetation as an integral component of the exposure model ensures that ambient dose reductions translate into genuine reductions in internal dose at the population level (Komatsu et al., 2021c; Merz et al., 2015b).

Insert Table 4 here.

Insert Figure 3 here.

4.4 The Risk Transfer: Short-Term Remediation versus Long-Term Stewardship Liabilities

While effective for rapid surface hazard abatement, the choice of soil-and-concrete capping converted a short-term remediation challenge into a long-term stewardship liability, a trade-off with significant policy implications for resource-constrained jurisdictions.

Modeling and field implementation. MicroShield 7.02 modeling evaluated three exposure-control scenarios for a 9×12 m source area to 60 cm depth at a conservative residual activity of 0.3 Bq/g: no cover, 10 cm soil cover, and 10 cm soil plus 10 cm concrete.

Parameter setting. Residual activity C_{res} was set to **0.3 Bq g⁻¹** as a **conservative upper bound** representing the upper tail of post-excavation residuals identified during delineation (see Supplement S2 §2.3). Base-case predictions in Table 5 correspond to = 0.3 Bq g⁻¹ and 10 cm soil + 10 cm concrete. To test robustness, **one-factor** sensitivity runs spanned **0.1–1.0 Bq g⁻¹** and cap thicknesses of **soil 5–15 cm** and **concrete 5–15 cm** (Supplement S2 §2.5). Base-case predictions reported in **Table 5** correspond to $C_{res}=0.3$ Bq g⁻¹ and **10 cm soil + 10 cm concrete**. Field implementation then opted for backfilling and concrete capping (1–11 September 2020) using regulator-verified clean fill. Post-work ambient measurements aligned with model projections, with surface dose rates falling to ≤ 0.0021 $\mu\text{Sv}\cdot\text{h}^{-1}$ for the soil-plus-concrete configuration, supporting capping as a conservative, climate-appropriate measure for rapid hazard abatement in a dense urban setting (see Table 5 and Figure 4) (Inoue et al., 2020, 2019; Kim et al., 2019). *Verification.* Ambient dose rates at **sentinel points** around the capped area were recorded immediately **before** capping and **within 48 h after** curing; **all points** showed declines consistent with MicroShield projections (≤ 0.0021 $\mu\text{Sv}\cdot\text{h}^{-1}$ for the soil-plus-concrete configuration). Per-point pre-capping logs were not retrievable after archival restructuring; therefore, verification is reported at the set level (see S2 §2.4).

No waterproof membrane was used; infiltration control was provided by the concrete cap, surface slope, and routine maintenance (e.g., crack sealing) (Yoshimura, 2022).

Life-cycle framing. While capping was appropriate for rapid dose abatement, it **transfers a short-term remediation cost into a long-term monitoring and institutional-control liability**. Jurisdictions should therefore apply a **life-cycle cost and institutional-readiness screen** when choosing between removal and containment, particularly where multi-year stewardship capacity is constrained.

Stewardship obligations. Capping isolates rather than eliminates the hazard. In tropical environments, micro-cracking, wet–dry cycling, root intrusion, and fluctuating groundwater can degrade barrier integrity and alter subsurface transport dynamics over time (Li et al., 2019; Revilla-Cuesta et al., 2024). Long-term stewardship is therefore obligatory: scheduled inspections for physical integrity (cracks, seepage, ponding), periodic surface dose scans, and, where indicated, shallow-soil or seep sampling to confirm stability. Institutional controls, land-use restrictions, durable site marking, and technical as-built documentation must accompany monitoring, with explicit performance triggers for re-opening active remediation options if safety margins erode (Padhye et al., 2023; Shi et al., 2024). Policy-wise, decision criteria should balance immediate ALARA gains from containment against life-cycle costs and institutional readiness for multi-year monitoring, clarifying when full removal is preferable to engineered isolation (Padhye et al., 2023; Shi et al., 2024). Figure 5 provides a conceptual schematic of the soil-plus-concrete barrier and associated checks. Given the absence of an impermeable layer, inspections for cracking and ponding during monsoon periods are especially critical to preserve performance. **Cross-cutting observation: role of rapid mapping and source recovery.** Initial GPS-integrated mapping captured ambient dose heterogeneity from ~ 0.5 to 149 $\mu\text{Sv}\cdot\text{h}^{-1}$ and guided targeted source recovery (Connor et al., 2018; Sato et al., 2020; Wainwright et al., 2019). Manual excavation with controlled screening on plastic sheeting minimized spread and preserved forensics; removing discrete fragments substantially reduced local fields and informed the subsequent choice of area-wide capping to address residual diffuse contamination.

Insert Table 5 here.

Insert Figure 4 here.

5. Lessons for Policy & Practice

The Batan Indah incident demonstrates that effective emergency response in resource-constrained tropical cities depends on the systemic fit between engineering choices and institutional capacity (Van Nguyen et al., 2023). Four cross-cutting lessons follow, synthesized from the analytical results in Section 4: surge-tolerant waste logistics (5.1), integrating ecological/internal pathways (5.2), adaptive crew protection (5.3), performance-based stewardship (5.4), and enabling data governance (5.5).

5.1 From Centralization to Surge-Tolerant Logistics

The waste surge generated by a localized operation stress-tested a national system designed for routine throughput. The ad-hoc occupation of corridors and pre-treatment rooms for drum staging was not merely a logistical inconvenience; it was a signal that safety controls begin to fragment when emergency volumes are routed through the same channels as routine work. A surge-tolerant architecture should therefore combine a national terminal facility with licensed regional interim stores and emergency-only flow paths that can be activated without disrupting baseline operations (Chen et al., 2021; Mei et al., 2022; Zhao et al., 2021). This transition from a fragile, single-node system to a resilient, hub-and-spoke network embodies the DRR principle of "Build Back Better," ensuring that post-incident recovery strengthens the critical infrastructure against future shocks.

Post-case signals of recurrence and policy impetus. In August 2025, the U.S. FDA advised against certain imported frozen shrimp processed by an Indonesian firm after CBP detected Cs-137 in shipping containers at multiple ports; FDA laboratory analysis confirmed $\sim 68 \text{ Bq kg}^{-1}$ Cs-137 in one detained breaded-shrimp sample—below the agency's Derived Intervention Level ($1,200 \text{ Bq kg}^{-1}$)—and placed the firm under a new import alert while recalls were recommended as a precaution. No product that tested positive entered U.S. commerce. In parallel ("FDA Advises Public Not to Eat, Sell, or Serve Certain Imported Frozen Shrimp from an Indonesian Firm | FDA," n.d.), BAPETEN reported Cs-137 contamination at a domestic frozen-shrimp plant, significant radiation at a nearby scrap-metal aggregation point, and two additional high-dose locations within a $\sim 2 \text{ km}$ radius, all secured pending handling and forensics. Taken together, these signals align with our central finding: localized radiological problems can re-emerge via industrial/logistics pathways and rapidly generate waste-handling surges that stress a purely centralized predisposal architecture (Badan Pengawas Tenaga Nuklir (BAPETEN), 2025). For industrial estates located tens of kilometers from PTLR–BATAN (e.g., $\sim 50 \text{ km}$ corridors in Greater Jakarta–Banten), longer haul distances, fewer licensed carriers, and the need to stage materials near operating factories would magnify overflow risk relative to the Serpong case—strengthening the case for licensed regional interim stores, mobile characterization/compaction units, emergency-only flow paths at the national facility, and cross-sector surveillance that explicitly covers seafood and scrap-metal nodes.

These observations motivate targeted policy pilots combining licensed regional interim stores and mobile characterization/compaction units in industrial corridors (see Section 5.6).

5.2 Beyond Surface Dose: Ecological and Food-Chain Pathways in Tropical Cities

Ambient dose mapping was indispensable for delineating work zones, but in humid tropical cities the combination of high rainfall, rapid plant turnover, and pervasive home-gardening creates short internal pathways that a purely external-dose lens under-weights (Komatsu et al., 2021a; Merz et al., 2015a; Velasco and Anjos, 2021b). In our case, edible foliage from affected yards reached very high Cs-137 activity ($\approx 39,867 \text{ Bq/kg}$ in turmeric leaves; see Section 4.3, Table 3;

Figure 3), while water samples were much lower (≈ 0.11 Bq/L)(Nguyen et al., 2022), a profile that directs early risk communication away from drinking-water and toward garden-to-table consumption (Merz et al., 2015a; Nakanishi and Sakuma, 2019). Whole-body counting (WBC) of 13 residents identified four with detectable body burdens, all linked by interview to consumption of home produce from within the zone; follow-up at ~ 4 months showed declines to at/below detection in three and below threshold in one, with the highest estimated committed effective dose of 0.12 mSv (see Supplement S3) (Yoshida-Ohuchi and Shinohara, 2020). These dynamics are consistent with sub-parcel heterogeneity in tropical urban soils, radiocesium concentrated in the upper 0–40 cm yet detectable at depth where cores were available, producing micro-hotspots of bioavailability and species-specific uptake that coarse zoning may miss (Ikehara et al., 2018; Imamura et al., 2020; Komatsu et al., 2021a; Manaka et al., 2022). Operationally, ecological pathways should be explicitly integrated from day 1 (Aung et al., 2015; Komatsu et al., 2021a; Velasco and Anjos, 2021b). Treating urban vegetation as part of the exposure model aligns engineering controls (surface-dose reduction) with actual reductions in internal dose at the population level and ensures that lifting advisories is evidence-based rather than purely time-based. Operationalization can proceed via a small indicator-species panel and targeted/mobile WBC services, with auditable de-escalation criteria (see Supplements S3–S4 and Section 5.6).

5.3 Adaptive Personnel Protection Under Field Constraints

Weekly cumulative doses remained low, but daily spikes among non-radiation staff revealed the limits of relying on averages when crews perform short, support tasks across sharp local gradients (Mussmann et al., 2024; Sailer et al., 2017).

During overlapping crises such as COVID-19 social restrictions, crew sizes and task sequencing change frequently, so rotation schedules must be adjusted on the day using a simple dose dashboard that visualizes peaks, not just totals (Loose et al., 2024; Vano et al., 2023). The broader lesson is that protecting mixed crews in dense urban sites is as much about task engineering and information flow as it is about limits (López et al., 2018).

5.4 Containment as Commitment: Criteria, Monitoring, and Triggers after Capping

Excavation followed by soil-plus-concrete capping produced rapid, verifiable reductions in surface dose, an appropriate choice for returning a dense residential site to safe use (Da Silva et al., 2018). But capping isolates rather than removes hazard, transferring risk management into a stewardship phase where tropical wet–dry cycling, micro-cracking, root intrusion, and shallow groundwater dynamics can erode barrier performance (Li et al., 2019; Revilla-Cuesta et al., 2024). Jurisdictions should therefore codify decision criteria that clarify when containment is acceptable and when full or partial removal is preferable, taking into account residual inventory, proximity to receptors, hydrogeological vulnerability, institutional capacity for multi-year monitoring, and life-cycle cost (Chen et al., 2023).

Proposed inspection periodicity and trigger thresholds are summarized in Supplement S4 to support adoption by local authorities.

These recommendations are synthesized in Figure 6, which links documented mechanisms to operational levers, pilots, and audit metrics.

Insert Figure 6 here.

5.5 Data Governance in Emergencies: Transparency, QA/QC-Lite, and Auditability

Emergency conditions, public pressure, and pandemic restrictions shaped what could be measured, when, and by whom (Wilkinson et al., 2016). In sum, the Batan Indah case affirms that preparedness for localized radiological incidents in tropical, resource-constrained cities is a system property. Surge-tolerant waste logistics, explicit treatment of internal ecological pathways, adaptive protection of mixed crews, and performance-based stewardship after containment are mutually reinforcing. Implemented together, and supported by transparent, audit-ready data practices, they move response from reactive control to adaptive governance, increasing both technical safety and institutional resilience in settings where the next incident may not be five kilometers from a national facility.

Provenance statements and QA/QC-lite templates (Supplements S2–S4) enable third-party auditability and inform the synthesis that follows in Section 6 (Conclusions) (Desvars-Larrive et al., 2020).

5.6 International Relevance and Transferability

The mechanisms highlighted here, single-node fragility under surge loads, short food-chain pathways in humid tropical cities, and the long-tail obligations that follow containment, generalize beyond Batan Indah (Tateda et al., 2024). Many archipelagic and rapidly urbanizing regions rely on one national predisposal node while hosting fragmented supply chains (seafood processing, scrap-metal aggregation) where Cs-137 problems can surface far from the original source term (see Section 5.1). A surge-tolerant logistics architecture, therefore pairs a national terminal with licensed regional interim stores, emergency-only flow paths at the national node, and mobile units for on-site compaction/basic characterization (Section 4.1). Early integration of food-chain pathways, indicator species plus targeted/mobile WBC, helps ensure that ambient-dose gains translate into real reductions in internal dose (Section 4.3) (Tateda et al., 2024). Where excavation plus soil-and-concrete capping is selected, performance-based stewardship with explicit triggers aligns containment choices with life-cycle costs and institutional capacity (Section 4.4) (Wang et al., 2021).

To operationalize these principles, two low-regret pilots are proposed—one industrial-corridor logistics pilot and one food-chain/WBC pilot—with outcomes and templates detailed in **Supplement S5** and summarized in Figure 6.

6. Conclusion

The Batan Indah incident demonstrates that effective management of localized technological emergencies, particularly in resource-constrained tropical cities, is not merely about executing individual technical tasks, but a system property requiring a fundamental shift from reactive control to adaptive governance. Our analysis reveals this through the lens of cascading risks and surge capacity failure, exposing four interconnected systemic vulnerabilities with broad implications for disaster risk reduction: First, a single, highly centralized waste architecture is intrinsically fragile under localized surges, a critical finding for critical infrastructure resilience planning globally. Second, in tropical urban settings, internal exposure pathways via home-garden vegetation are material risks often missed by standard external-dose assessments, highlighting a dangerous blind spot in urban risk mapping. Third, personnel protection in complex, overlapping crises requires adaptive task engineering and real-time information, lessons applicable to managing diverse field operations under duress. Fourth, remediation via containment (excavation–capping) shifts immediate risk but creates a long-term stewardship liability, a core governance challenge in post-incident recovery worldwide.

By framing these findings within the context of cascading risks, the novelty of this study lies in its practice-oriented analytical framework that connects technical safety, operational feasibility

under constraint, and long-term sustainability. This framework is applicable to managing diverse mid-scale urban technological incidents. Practically, the study argues for resilient infrastructure (surge-tolerant logistics), explicit integration of ecological pathways into early warning systems, adaptive protection of mixed crews, and codified stewardship criteria after containment—principles vital for strengthening urban systemic resilience. Furthermore, this study provides an important methodological contribution by demonstrating that transparent and technically robust evaluation is possible and necessary despite post-incident data loss, a common reality in disaster review. Rather than being a mere limitation, these constraints underscore our core argument: adaptive and auditable systems are critical for both operational response and improving future practices.

Taken together, these results offer crucial insights for moving urban emergency response from reactive control toward proactive risk governance. The lessons from Batan Indah extend beyond radiological hazards, providing a template for building resilient systems that can manage unexpected surges and contain cascading consequences, thereby ensuring public safety and functional infrastructure in an era of increasing urban and technological risks.

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Table Captions

Table 1. Comparative framing of urban radiological contexts by problem class, system stress relative to capacity, and transferable lessons. *Note: "System-stress" is assessed relative to available institutional/logistical capacity at the time, not absolute release/activity. Read this comparison as complementary lenses: Batan Indah interrogates surge-tolerance and decentralized logistics under tropical, resource-constrained conditions, questions that the landmark Goiânia and Fukushima cases, while invaluable, do not resolve for mid-scale urban incidents.*

Table 2. Radioactive Waste Inventory and Staging Path (Batan Indah Operation). *Footnote: Steel drums are 100 L; HDPE drums are 150 L.*

Table 3. Personnel Dose Summary During the Remediation Operation. ** Daily mean computed as weekly cumulative divided by assumed 6–5 active workdays during the reporting week (PSBB context). † No facility-specific weekly administrative limit documented; % of admin weekly limit not reported. Weekly compliance assessed against the annual limit and ALARA. ‡ 142 μSv / 20,000 μSv = 0.71% (radiation workers); 15 μSv / 1,000 μSv = 1.50% (non-radiation staff). All values remained well within applicable limits, while the day-to-day spikes reinforce the need to manage peaks operationally through task design and real-time alarms.*

Table 4. Cs-137 Activity Concentrations in Representative Matrices (5 Feb 2020). *Notes: Water value was reported as Bq/kg in the technical report; treated here as Bq/L assuming $\rho \approx 1$ kg/L. All values and uncertainties are as reported; MDC at 95% confidence.*

Table 5. MicroShield 7.02 predictions for surface dose rates under alternative cover scenarios. *Notes: Base-case predictions at residual activity 0.3 Bq g⁻¹ are shown. Baseline ("No cover") =*

0.0515 $\mu\text{Sv}\cdot\text{h}^{-1}$; percentage reductions are computed relative to this baseline. Sensitivity analyses varying residual activity (**0.1–1.0 Bq g⁻¹**) and cap thicknesses (**soil 5–15 cm; concrete 5–15 cm**) are documented in Supplement S2 §2.5.

Figure Captions

Figure 1. Site context of the Batan Indah Cs-137 incident in South Tangerang (Greater Jakarta), showing the worksite and the road connection (≈ 5 km) to PTLR–BATAN/BRIN Serpong. North arrow and 1–2 km scale bar included. Basemap: OpenStreetMap contributors (© ODbL). CRS: WGS84 / EPSG:4326.

Figure 2. Waste composition (a) and logistics flow (b) during the Batan Indah operation. Counts and pathways reflect consolidated records; overflow required corridor use and a semi-permanent transit shelter adjacent to Interim Storage-2 (IS-2). Thresholds shown as $\leq 10 \mu\text{Sv}\cdot\text{h}^{-1}$ are operational for field control.

Figure 3. Cs-137 activity in selected vegetation (log scale; Bq/kg). Values correspond to samples collected on 5 Feb 2020.

Figure 4. Predicted surface dose rates for modeled control scenarios (MicroShield 7.02).

Figure 5. Conceptual cross-section of soil-plus-concrete capping (no membrane) and stewardship checks (not to scale). A ~ 10 cm soil cap and ~ 10 cm concrete slab overlies the residual source zone (0–60 cm). Infiltration control relied on the concrete cap and surface drainage; no waterproof membrane was installed.

Figure 6. Policy implications framework. Each column links a problem class to documented evidence (Sections 4.1, 4.3, 4.4), specific policy levers, operational pilot concepts, and audit metrics. The framework emphasizes surge tolerance in waste logistics, explicit treatment of tropical food-chain pathways, and performance-based stewardship following containment. Full pilot protocols and templates are provided in Supplement S5

Table 1. Comparative framing of urban radiological contexts by problem class, system stress relative to capacity, and transferable lessons

Context	Problem class (scale × constraints)	Primary response objective	Dominant strategy/approach	System-stress relative to capacity	Key transferable lesson
Batan Indah (2020, Indonesia; dense tropical urban)	Mid-scale, high constraints; single-node waste architecture	Rapid hazard abatement & public reassurance under COVID-19	Targeted source recovery; soil excavation + capping ; centralized transport to national node	Very high (906 drums quickly saturated a sole national predisposal node)	Surge-tolerant, decentralized predisposal; mobile compaction/characterization; integrate urban food-chain pathways & WBC early
Goiânia (1987, Brazil; urban orphan-source)(Obrador et al., 2022; Sakamoto-Hojo, 2018; Tessaro et al., 2023)	Localized acute event with urgent medical dimension	Source recovery & medical management	Hotspot removal; demolition of highly contaminated structures; triage & follow-up	High (improvised early logistics; intense public anxiety)	Orphan-source forensics; crisis risk communication; rapid hotspot logistics
Fukushima Daiichi (2011, Japan; national scale)(Bin Feng et al., 2022; Hirose and Povinec, 2022; Onda et al., 2020)	Catastrophic, wide-area fallout with strong national mobilization	Protect public & recover land use	Zoning/relocation; extensive topsoil removal; bagging & interim storage; long-term recovery	Extreme, but buffered by national capacity	Long-horizon stewardship; large-volume waste governance; land-recovery planning

Note: “System-stress” is assessed relative to available institutional/logistical capacity at the time, not absolute release/activity. Read this comparison as complementary lenses: Batan Indah interrogates surge-tolerance and decentralized logistics under tropical, resource-constrained conditions, questions that the landmark Goiânia and Fukushima cases, while invaluable, do not resolve for mid-scale urban incidents.

Table 2. Radioactive Waste Inventory and Staging Path (Batan Indah Operation)

Category	Count	Container	Primary content	Initial staging	Overflow / mitigation
Soil	487	100 L steel	Contaminated soil	IS-1 (Bldg 52)	Corridor (Bldg 53); transit shelter built
Soil	375	150 L HDPE	Contaminated soil	IS-1 (Bldg 52)	Corridor (Bldg 53); transit shelter built
Vegetation	25	150 L HDPE	Cut biomass	IS-1 (Bldg 52)	Corridor / temporary bays

PPE	19	100 L steel	Used protective equipment	IS-1 (Bldg 52)	Corridor / temporary bays
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Footnote: Steel drums are 100 L; HDPE drums are 150 L

Table 3. Personnel Dose Summary During the Remediation Operation

Group	N	Highest daily dose (μSv)	Daily mean (μSv)*	Weekly cumulative (μSv)	% of admin weekly limit†	% of annual regulatory limit‡	Notes
Radiation workers	173	87	23.7–28.4	142	—	0.71%	—
Non-radiation staff	14	7	2.5–3.0	15	—	1.50%	—

* Daily mean computed as weekly cumulative divided by assumed 6–5 active workdays during the reporting week (PSBB context).

† No facility-specific weekly administrative limit documented; % of admin weekly limit not reported. Weekly compliance assessed against the annual limit and ALARA.

‡ $142 \mu\text{Sv} / 20,000 \mu\text{Sv} = 0.71\%$ (radiation workers); $15 \mu\text{Sv} / 1,000 \mu\text{Sv} = 1.50\%$ (non-radiation staff).

All values remained well within applicable limits, while the day-to-day spikes reinforce the need to manage peaks operationally through task design and real-time alarms

Table 4. Cs-137 Activity Concentrations in Representative Matrices (5 Feb 2020)

Matrix	Sample quantity	Activity concentration	Uncertainty (95%)	MDC (95%)	Unit	Notes
Water (soak pit)	1.00 L	0.11	0.16	0.16	Bq/L	Reported as Bq/kg; treated as Bq/L ($\rho \approx 1 \text{ kg/L}$)
Turmeric leaves	0.07 kg	39,866.67	3,758.85	2.40	Bq/kg	
Taro leaves	0.19 kg	780.75	79.41	0.84	Bq/kg	
Soursop (fruit)	0.45 kg	2,146.96	204.18	0.36	Bq/kg	
Lime (fruit)	0.06 kg	2,346.11	225.80	0.75	Bq/kg	
Grass	0.39 kg	5,768.42	543.56	0.30	Bq/kg	
Leaves (unspecified)	0.22 kg	648.34	66.38	0.76	Bq/kg	

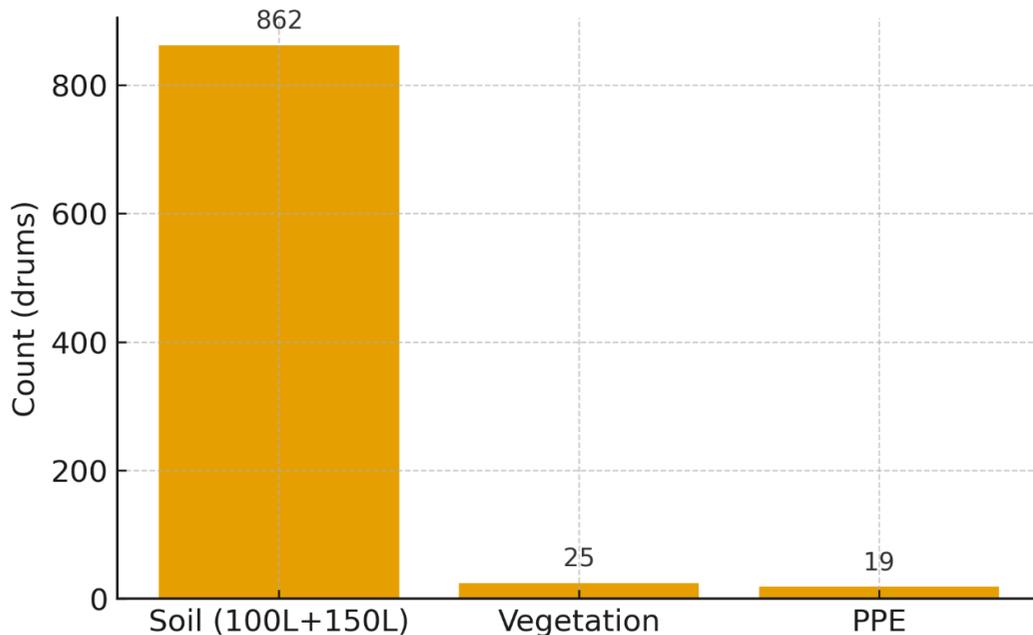
Notes: Water value was reported as Bq/kg in the technical report; treated here as Bq/L assuming $\rho \approx 1 \text{ kg/L}$. All values and uncertainties are as reported; MDC at 95% confidence.

Table 5. MicroShield 7.02 predictions for surface dose rates under alternative cover scenarios

Scenario	Cover configuration	Assumptions	Predicted surface dose ($\mu\text{Sv}\cdot\text{h}^{-1}$)	Reduction vs baseline (%)	Notes
No cover	None	Area 9×12 m; depth 60 cm; residual 0.3 Bq/g; soil $\rho\approx 1.3\text{ g/cm}^3$; concrete $\rho\approx 2.35\text{ g/cm}^3$	0.0515	0.0	Baseline at residual activity 0.3 Bq/g
10 cm soil cover	Soil 10 cm	Area 9×12 m; depth 60 cm; residual 0.3 Bq/g; soil $\rho\approx 1.3\text{ g/cm}^3$; concrete $\rho\approx 2.35\text{ g/cm}^3$	0.0152	70.5	Backfill with verified clean fill
10 cm soil + 10 cm concrete	Soil 10 cm + Concrete 10 cm	Area 9×12 m; depth 60 cm; residual 0.3 Bq/g; soil $\rho\approx 1.3\text{ g/cm}^3$; concrete $\rho\approx 2.35\text{ g/cm}^3$	0.0021	95.9	Capping executed 1–11 Sep 2020
<p>Notes: Base-case predictions at residual activity 0.3 Bq g⁻¹ are shown. Baseline (“No cover”) = 0.0515 $\mu\text{Sv}\cdot\text{h}^{-1}$; percentage reductions are computed relative to this baseline. Sensitivity analyses varying residual activity (0.1–1.0 Bq g⁻¹) and cap thicknesses (soil 5–15 cm; concrete 5–15 cm) are documented in Supplement S2 §2.5.</p>					



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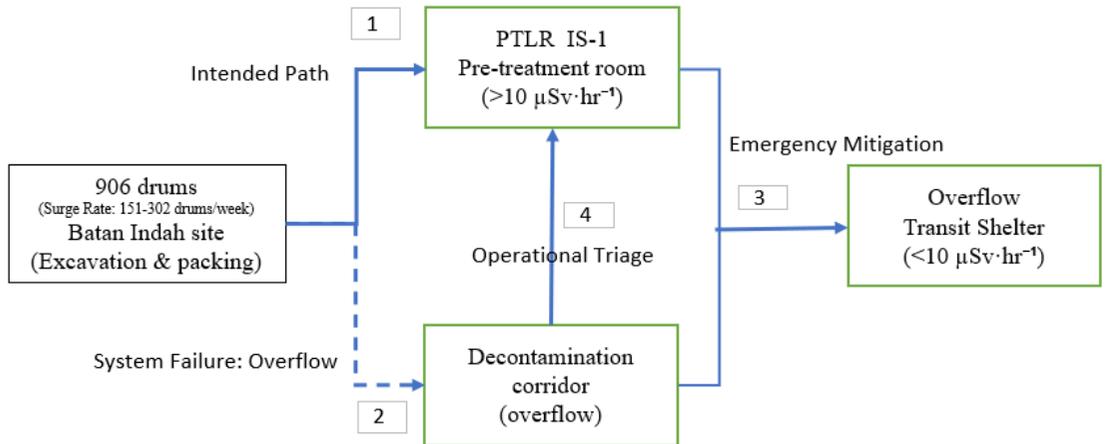


Figure 2. Waste composition (a) and logistics flow (b) during the Batan Indah operation. Counts and pathways reflect consolidated records; overflow required corridor use and a semi-permanent transit shelter adjacent to Interim Storage-2 (IS-2). Thresholds shown as $\leq 10 \mu\text{Sv}\cdot\text{h}^{-1}$ are operational for field control.

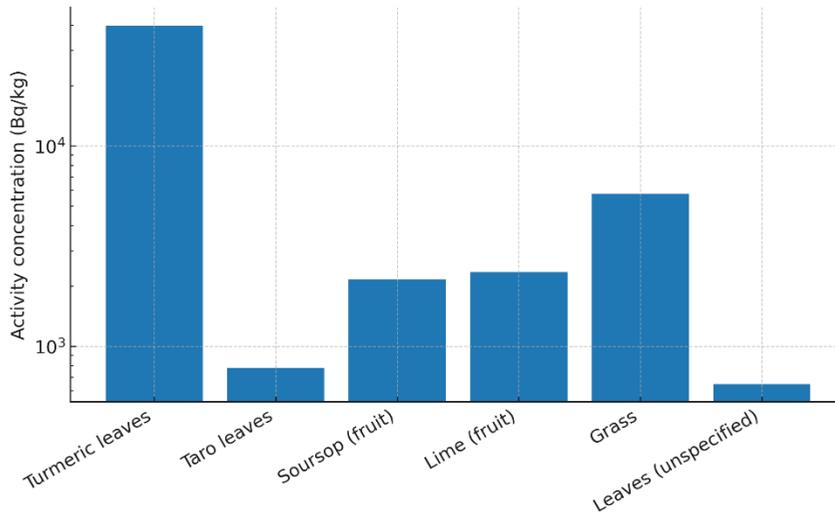


Figure 3. Cs-137 activity in selected vegetation (log scale; Bq/kg). Values correspond to samples collected on 5 Feb 2020.

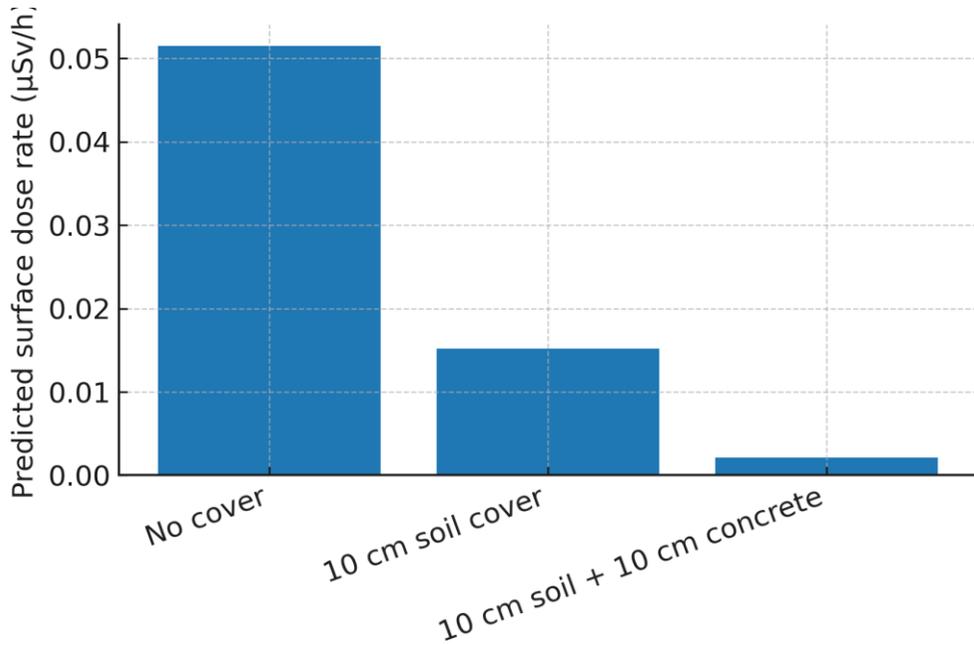


Figure 4. Predicted surface dose rates for modeled control scenarios (MicroShield 7.02).

Scheduled Inspection:
Cracks, seepage, ponding

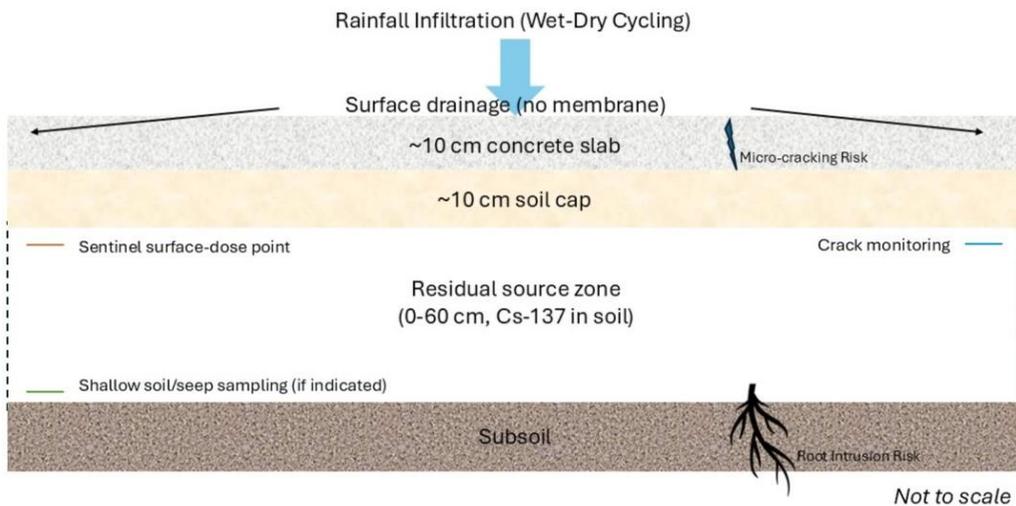


Figure 5. Conceptual cross-section of soil-plus-concrete capping (no membrane) and stewardship checks (not to scale). A ~10 cm soil cap and ~10 cm concrete slab overlies the residual source zone (0–60 cm). Infiltration control relied on the concrete cap and surface drainage; no waterproof membrane was installed.

	A. Surge & centralization	B. Internal dose & food chain	C. Containment & stewardship
Gap	Single-node predisposal architecture lacks surge tolerance.	External-dose mapping under-weights tropical urban food pathways.	Criteria and triggers after capping are under-specified.
Evidence	906 drums; overflow to corridors/IS-1; proximity dividend non-generalizable. (Section 4.1; Fig 1–2; Table 1)	Turmeric $\approx 3.99 \times 10^4$ Bq/kg; water ~ 0.11 Bq/L; 4/13 WBC positives; follow-up declines; CED max 0.12 mSv. (Section 4.3; Table 3; Fig 3)	MicroShield scenarios; soil+concrete cap $\rightarrow \leq 0.0021 \mu\text{Sv}\cdot\text{h}^{-1}$; tropical degradation risks. (Section 4.4; Table 4; Fig 4–5)
Policy levers	Hub-and-spoke: licensed regional interim stores; emergency-only flows at the national node; mobile compaction/characterization.	Indicator-species panel; temporary consumption advisories; targeted/mobile WBC.	Performance-based stewardship: as-built records; inspection cadence; trigger thresholds; graded responses.
Pilot	Industrial-corridor pilot (30–60 km from national node).	Food-chain/WBC pilot in two dense wards.	GIS registry of capped sites + trigger-based O&M playbook.
Metrics	Detection \rightarrow staging time; handling time/transfer; overflow incidence; near-misses.	Indicator-plant trends; WBC positivity (3–6 mo); lag advisory \rightarrow dose decline.	Sentinel surface-dose trend; crack/seep thresholds; inspection compliance.

Note: Figure 6 synthesizes gaps, evidence, policy levers, pilots, and audit metrics. Full pilot protocols and templates are provided in Supplement S5.

Figure 6. Policy implications framework. Each column links a problem class to documented evidence (Sections 4.1, 4.3, 4.4), specific policy levers, operational pilot concepts, and audit metrics. The framework emphasizes surge tolerance in waste logistics, explicit treatment of tropical food-chain pathways, and performance-based stewardship following containment. Full pilot protocols and templates are provided in Supplement S5.