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BATTERY FIREWATER AS AN EMERGING ENVIRONMENTAL HAZARD: EVIDENCE SYNTHESIS AND THE C5 CONTAINMENT–TREATMENT FRAMEWORK FOR LITHIUM-ION BATTERY INCIDENTS

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ABSTRACT

The rapid deployment of lithium-ion batteries in electric vehicles, stationary energy-storage systems, consumer products and waste streams has created an environmental problem that is insufficiently integrated into conventional fire-safety practice: contaminated firefighting runoff. Water remains one of the most important suppression and cooling media for lithium-ion battery incidents, yet contact with thermally damaged cells, combustion products and deposited particulates can generate a chemically complex wastewater containing fluoride, lithium, nickel, cobalt, manganese, copper, aluminum, organic electrolyte residues, soot-associated contaminants and per- and polyfluoroalkyl substances. This structured critical review synthesizes experimental, ecotoxicological, toxicological and field evidence available through September 2026 and organizes it using a source–pathway–receptor model. The evidence indicates that environmental risk is governed not simply by battery chemistry but by incident scale, state of charge, degree of cell rupture, suppression method, water volume, internal flushing, post-fire immersion, drainage connectivity and containment. The study introduces the five-stage C5 framework—Contain, Characterize, Classify, Clean and Confirm—and a four-level B0–B3 incident classification to translate evidence into operational decisions. A contaminant-oriented treatment architecture combining solids separation, precipitation/coagulation, ion exchange or adsorption, membrane polishing and controlled residual management is proposed. Battery firewater should be treated as potentially contaminated industrial wastewater until site-specific characterization demonstrates an appropriate disposition route. The framework connects battery fire safety, emergency response, environmental engineering and water-quality management without discouraging essential life-safety suppression.

Keywords: Lithium-ion battery fire; Firefighting runoff; Firewater; Ecotoxicity; PFAS; Wastewater treatment

1 INTRODUCTION

Lithium-ion batteries (LIBs) now underpin electric mobility, stationary electrical storage, portable electronics, industrial equipment and renewable-energy infrastructure. Their high energy density and long cycle life are accompanied by a distinctive failure mode: thermal runaway, in which exothermic reactions accelerate cell heating, venting, flammable-gas production and, in severe cases, fire or explosion. Quantitative testing has shown that battery fires can release substantial hydrogen fluoride (HF), while broad meta-analyses demonstrate large variation in heat release and gas composition across cell geometry, chemistry, state of charge and abuse condition [1,2]. More recent synthesis has reinforced that toxic and flammable off-gas cannot be treated as a fixed property of a generic "lithium-ion battery" because chemistry and test conditions materially change both volume and composition [3].

The water problem begins after suppression water performs its primary safety function. Water is an efficient heat sink and is often operationally necessary to cool exposed modules, prevent propagation and protect neighboring structures. Yet water that contacts ruptured cells, electrolyte, cathode debris, soot, deposited aerosols and combustion products can become a multi-contaminant liquid. Large-scale battery and battery-electric-vehicle fire tests have measured elevated metals, fluoride, organic contaminants and per- and polyfluoroalkyl substances (PFAS) in extinguishing water, alongside marked acute aquatic toxicity [4]. Vehicle-scale investigations have likewise shown that firefighting, sprinkling and storage waters can acquire lithium, fluoride and cathode-associated metals [5].

Module-scale suppression experiments now provide converging evidence. NMC battery tests have identified nickel, manganese, cobalt, lithium, aluminum and carbonaceous matter in runoff [6], and comparisons among water mist, water-based additives and carbon dioxide demonstrate that suppression effectiveness and the environmental properties of resulting residues must be evaluated together [7]. In 2026, realistic rubbish-truck fire trials found fluoride and multiple metals in runoff at concentrations exceeding the freshwater trigger values used by the investigators [8]. Long-contact scenarios may be still more consequential: controlled immersion of damaged electric-vehicle battery systems has shown progressive leaching, high conductivity, very high lithium and fluoride concentrations and severe acute ecotoxicity over extended storage [9].

PFAS adds another layer of complexity. PFAS have been measured in battery-fire extinguishing water [4] and in soot generated during cell thermal runaway [10]. This establishes a plausible sequence in which airborne particulate deposition becomes a secondary aqueous pathway after rainfall or wash-down. The problem is no longer limited to laboratory testing. Large-scale BESS suppression experiments published in 2026 reported that all sampled firewater runoff exceeded the contamination criteria applied in that study [11], while field measurements following the 2025 Moss Landing BESS fire detected transient surface enrichment of nickel, manganese and cobalt in nearby wetland soils consistent with NMC cathode material [12].

Fire-suppression reviews identify water and water mist as effective cooling strategies [13], broad EV fire reviews characterize propagation and reignition hazards [14], and damaged-EV recovery guidance emphasizes risks that persist after extinguishment [15]. Environmental runoff, however, is still rarely treated as a co-equal design variable.

This review therefore asks a practical interdisciplinary question: how should battery firewater be managed once water has been selected for legitimate life-safety and cooling reasons? The contribution is fourfold. First, it synthesizes evidence from cells, modules, EVs, BESS facilities, waste fires, toxicological studies and field incidents. Second, it introduces a source–pathway–receptor model that explicitly includes delayed wash-off and long-duration immersion. Third, it proposes a four-level battery-firewater classification (B0–B3) and the operational C5 sequence—Contain, Characterize, Classify, Clean and Confirm. Fourth, it links contaminant classes to a staged treatment train and proposes a minimum reporting set for future battery-firewater experiments. The framework is intentionally conservative: it does not recommend withholding water where suppression is required; it recommends engineering the site and response so the water can be contained, characterized and managed afterward.

2 MATERIALS AND METHODS

A structured critical evidence synthesis was undertaken using peer-reviewed journal articles, indexed bibliographic records, recognized standards and government incident-response resources available through 8 September 2026. Search concepts combined "lithium-ion battery fire," "thermal runaway," "extinguishing water," "firewater runoff," "battery fire wastewater," "fluoride," "PFAS," "metals," "ecotoxicity," "electric vehicle fire," "battery energy storage system fire," "immersion," "leaching," "wastewater treatment" and related terms. Greater evidentiary weight was assigned to studies that directly measured liquid runoff, post-fire residues, soot/particulate composition, environmental deposition, organism toxicity or treatment performance.

Studies were included when they contributed to at least one of five evidence domains: (i) source chemistry and emission mechanisms; (ii) firewater or post-fire water measurements; (iii) ecological or human-health effects; (iv) field-scale environmental fate; or (v) treatment and operational management. Purely computational fire simulations were not used as primary evidence for water-quality conclusions. Reviews were used to contextualize thermal-runaway variability and treatment technology, while standards and government guidance were used to evaluate the maturity of current incident-management practice.

Conventional pooled meta-analysis was not attempted because the available firewater studies differ markedly in battery chemistry, nominal energy, state of charge, non-battery fuel load, suppression technology, water volume, collection fraction, sampling time and analytical method. Pooling concentration values without harmonized denominators would create false precision. Instead, the evidence was synthesized mechanistically and compared across incident scales. Where numerical values are cited, they remain associated with the conditions of the original experiment and are not presented as universal battery-firewater concentrations.

Framework development mapped the evidence to source → pathway → receptor controls and matched observed contaminant classes to established treatment processes. The resulting C5 and B0–B3 schemes are synthesis-based proposals that require prospective validation before prescriptive use.

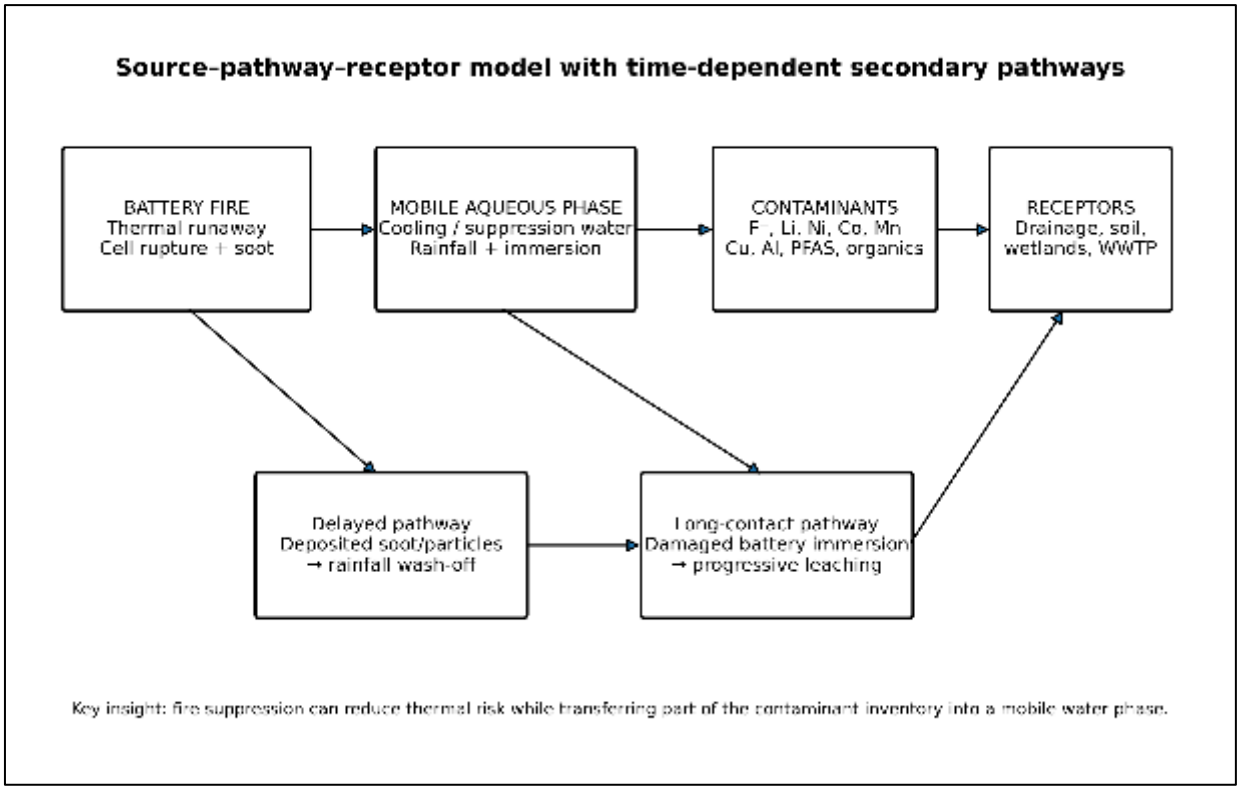

Figure 1: Original source–pathway–receptor model for lithium-ion battery firewater, including delayed rainfall wash-off and long-contact immersion pathways. Source: authors' synthesis of the evidence reviewed in [4–12].

3 FORMATION AND COMPOSITION OF BATTERY FIREWATER

3.1 From cell chemistry to a mobile aqueous phase

A LIB is an assembly of chemically dissimilar materials rather than a homogeneous fuel. NMC and NCA chemistries contain nickel, cobalt and manganese or aluminum-bearing cathode materials; LFP cells contain iron-phosphate cathodes; copper and aluminum current collectors are common; electrolyte systems typically contain lithium salts and organic carbonate solvents; and fluorinated binders, separators or additives may be present. During thermal runaway, high temperature, venting, rupture and combustion redistribute these materials among gas, aerosol, soot, coarse fragments and residual cell components. Aerosol studies have identified complex particle morphologies and metal-bearing material emitted during battery explosions [16]. Scale-up experiments from cells to second-life modules further demonstrate that emitted gases, heat and secondary explosion hazards can change with system scale [17].

Water can scavenge and mobilize thermal-runaway particles that would otherwise remain airborne or settle as dry deposition. A 2024 review describes carbon-, carbonate-, metal-oxide- and metal-containing particles [18], while recent toxicology identifies chemistry-dependent heavy metals and cellular injury responses [19]. The same particulate inventory relevant to inhalation can therefore become a water-quality problem after spray capture, wash-down or rainfall.

Fluoride remains one of the most reproducible battery-specific signals. The commonly used salt $LiPF_6$ can decompose and hydrolyze through pathways that generate HF and other phosphorus-fluorine species. Larsson et al. measured approximately 20–200 mg HF per Wh of nominal capacity in the commercial cells they tested [1]. In firewater, fluoride has been detected after vehicle and pack testing [4,5], module suppression [6], and waste-vehicle fire trials [8]. Internal battery flushing can further increase contact between water and damaged electrochemical material, which helps explain why post-flush concentrations in some experiments exceed those in free runoff [4].

Transition metals and lithium derive from electrode materials and current collectors. Their environmental relevance depends on total concentration, dissolved/particulate partitioning, pH, water hardness and receiving-water chemistry. NMC systems are particularly recognizable because Ni, Mn and Co can co-occur with Li, Cu and Al. In field settings this elemental pattern can act as a fingerprint: the post-Moss-Landing wetland study found a Ni:Co relationship consistent with NMC cathode material and observed a shallow, spatially patchy surface deposit [12].

3.2 PFAS, organic constituents and mixed-contaminant behavior

The organic fraction is less standardized than the inorganic fraction because a fire scene may include electrolyte solvents, vehicle polymers, building materials, cable insulation, combustion byproducts, firefighting additives and background contaminants. Quant et al. measured PFAS in extinguishing water and observed an increase after battery flushing [4]. Willstrand et al. later detected PFAS in soot from every cell thermal-runaway test in their experimental series, with short-chain compounds among the most prominent analytes [10]. These findings support a direct battery-related contribution while also underscoring the need for source attribution at complex incidents.

The mixture perspective is critical. Metals, fluoride, dissolved organics, suspended cathode particles, soot and PFAS do not occur in isolation. They can compete for sorption sites, affect pH and conductivity, foul membranes or alter apparent toxicity. This is one reason a treatment process optimized for a single laboratory contaminant may underperform on authentic firewater. It is also why chemical analysis should be supplemented by whole-effluent toxicity for selected high-consequence incidents rather than assuming that compliance for a small analyte list captures the total ecological effect.

3.3 Representative evidence across incident scales

Table 1: Representative direct evidence of lithium-ion battery firewater or post-fire environmental contamination.

Study / year	Scenario	Key measured finding	Interpretive significance
Quant et al., 2023 [4]	Vehicle and battery-pack fire tests	High aquatic toxicity; metals, fluoride and PFAS detected; PFAS increased after pack flushing	Shows runoff is a mixed toxic effluent and that internal flushing can intensify contamination
Held et al., 2022 [5]	EV battery thermal-runaway testing	Lithium, fluoride and cathode-related metals contaminated firefighting/storage waters	Demonstrates post-fire water management is part of EV incident recovery
Bordes et al., 2024 [6]	NMC module suppression	Ni, Mn, Co, Li, Al and carbonaceous contamination in runoff	Confirms battery-material transfer to liquid at module scale
Ubaldi et al., 2024 [7]	NMC pouch cells, three extinguishing agents	Water-based agents cooled effectively; liquid residues contained metals above aquatic-risk limits used by authors	Shows suppression performance and residue hazard should be optimized together
Jalali et al., 2026 [8]	Realistic rubbish-truck battery fires	Fluoride reached 6 mg/L; Al, Cu, Mn and Ni exceeded selected freshwater trigger values	Extends problem to waste-sector incidents with heterogeneous fuel

Meraner et al., 2026 [11]	Large-scale BESS room experiments	All sampled firewater runoff exceeded contamination limits applied in the study	Direct large-scale evidence that BESS firewater requires containment planning
Aiello et al., 2025 [12]	Field monitoring after Moss Landing BESS fire	Transient Ni/Mn/Co enrichment in adjacent wetland surface soils	Demonstrates real-world deposition and remobilization potential
Pokorna-Krayzelova et al., 2026 [9]	Long-term damaged-EV-battery immersion	Progressive leaching; very high Li and F in severe conditions; strong Daphnia toxicity	Identifies immersion water as a distinct long-duration leachate category

4 ECOTOXICOLOGICAL AND HUMAN-HEALTH IMPLICATIONS

Ecotoxicity data provide a bridge between chemistry and environmental consequence. In the large-scale extinguishing-water study by Quant et al., all tested waters exhibited high toxicity toward the selected aquatic species [4]. The result is important because no single analyte necessarily explains the biological response. Whole effluent can contain dissolved ions, particulate metals, acidic or alkaline species, high conductivity, electrolyte decomposition products, soot and persistent organics simultaneously. Long-duration leachate testing has strengthened this concern by demonstrating severe toxicity after prolonged contact between damaged EV battery systems and water [9].

Human-health priorities differ by phase of the incident. During active thermal runaway, inhalation of toxic and flammable gases, smoke and particulates remains more urgent than direct contact with runoff. HF is a recognized acute inhalation hazard, and the NIOSH Immediately Dangerous to Life or Health value is 30 ppm [25]. Thermal-runaway toxicology studies now indicate that particulate emissions can also produce biological effects that depend on battery chemistry [19]. After fire control, however, exposure shifts toward firefighters, recovery personnel, towing operators, environmental contractors and wastewater workers who may contact contaminated water, sludge, PPE, pumps or wash-down residues.

This phase transition argues for two separate safety plans: an acute fireground plan centered on respiratory protection, isolation and thermal control, and a post-fire environmental/occupational plan centered on contaminated-water containment, sampling, decontamination and waste handling. Conflating the two can lead to the mistaken assumption that a fire is “over” once temperature stabilizes.

5 ENVIRONMENTAL FATE: DIRECT RUNOFF, WASH-OFF AND IMMERSION

A useful environmental model must account for time. Direct runoff is the obvious pathway: water applied during suppression reaches floors, roads, containment areas or drains. A second pathway begins with atmospheric transport. Battery-derived particles can settle beyond the immediate fire footprint, and subsequent precipitation can mobilize deposited material. The Moss Landing wetland study observed strong surface enrichment shortly after the event followed by declines associated with precipitation and tidal inundation, consistent with redistribution from the shallow surface layer [12].

A third pathway is deliberately created during damaged-battery management. Immersion or flooded-container storage has been used in some EV recovery practices to control delayed thermal events. Yet prolonged water contact may progressively extract soluble constituents. The 112-day leaching study available in 2026 reported conductivity characteristic of strong industrial leachates, lithium up to approximately 1.54 g/L and fluoride up to approximately 218 mg/L in the most severe condition, together with pronounced acute ecotoxicity [9]. Such values should not be generalized to every EV incident, but they demonstrate why immersion water cannot be assumed equivalent to short-duration fireground runoff.

Government response practice increasingly reflects this pathway logic. The U.S. EPA’s current BESS guidance recommends minimizing, containing or redirecting runoff from water application where possible, while explicitly maintaining fire-spread control as the response priority [32]. At Moss Landing, EPA reported that suppression water was captured in an on-site tank, sampled and then disposed at an off-site facility; the site also uses drainage and lined collection controls to manage rainwater during recovery work [33]. These real-response examples support the engineering principle at the center of this review: the most reliable intervention is often to break the pathway between contaminated water and an uncontrolled receptor.

6 THE C5 CONTAINMENT–TREATMENT FRAMEWORK

The proposed C5 framework translates the evidence into five sequential control stages. It is not intended to supersede incident command or fire-code requirements. Rather, it adds an environmental decision layer that can be pre-planned and activated once it is safe to do so.

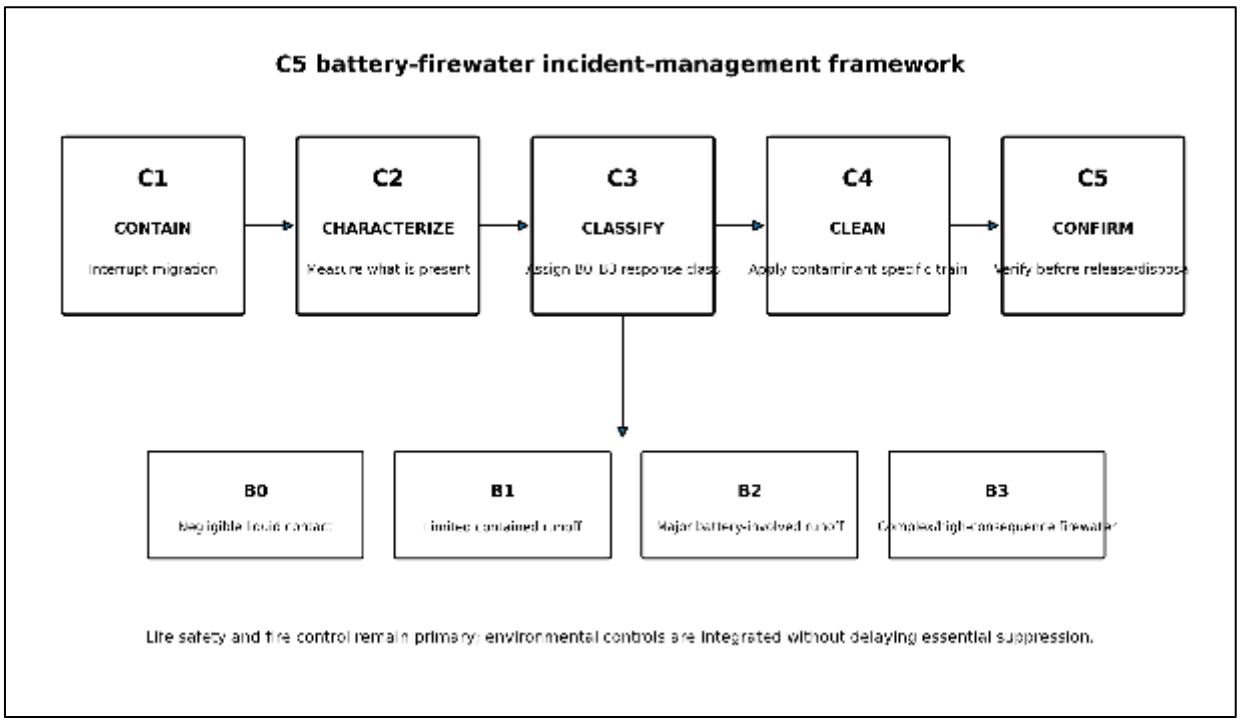

Figure 2: Original C5 incident-management framework and B0–B3 battery-firewater classification proposed in this review.

6.1 C1 - Contain

Containment is the highest-leverage environmental action because it can reduce off-site consequences without requiring perfect knowledge of composition. Measures may include drain covers, remotely or manually actuated stormwater valves, portable berms, retention basins, lined sumps, vacuum recovery, temporary tanks and predesignated sacrificial containment zones. For stationary BESS, these features can be designed into the site rather than improvised during an emergency.

Containment volume should be scenario based. Facilities should consider the credible duration and flow of cooling water, fixed-system discharge, rainfall contribution, expected leakage and practical tanker availability. The goal is not to guarantee zero release under every extreme scenario; it is to materially reduce the probability that contaminated water immediately enters a storm drain, wetland or surface-water receptor.

6.2 C2 - Characterize

Captured water should be presumed contaminated until data support a disposition decision. A battery-oriented screening suite should consider pH, conductivity, turbidity, total suspended solids, fluoride, lithium, chemistry-relevant cathode metals, copper and aluminum. PFAS analysis is warranted when incident scale, battery design, soot deposition or firefighting materials make fluorinated contaminants plausible. Total organic carbon or chemical oxygen demand can provide a broad measure of organic loading. For major incidents, filtered and unfiltered metal measurements help distinguish dissolved from particulate transport, while acute ecotoxicity can reveal mixture effects that targeted chemistry misses.

6.3 C3 - Classify

A practical response system needs a triage step before detailed treatment design. The proposed B0–B3 classes use observable incident characteristics rather than an unvalidated energy-capacity threshold:

- B0 - negligible liquid-contact event: little or no suppression water and no meaningful drainage pathway.

- B1 - limited contained runoff: small battery involvement, short-duration water contact, complete capture and no evidence of extensive cell rupture.
- B2 - major battery-involved runoff: traction-battery or multi-module involvement, substantial suppression water, visible cell rupture, internal flushing or uncertain capture fraction.
- B3 - complex/high-consequence firewater: BESS, battery warehouse, recycling/waste facility, prolonged immersion, large holding basin or confirmed high contaminant loading.

The class determines the default level of environmental specialist involvement, analytical breadth and documentation. B0 may require only ordinary debris management; B1 should normally be characterized before discharge; B2 warrants formal containment and a treatment/disposal decision; and B3 should be managed as industrial or potentially hazardous wastewater until characterization and applicable regulation establish otherwise.

6.4 C4 - Clean

No universal single-process technology can remove all battery-firewater contaminants. Metals, fluoride, PFAS, dissolved organics and suspended cathode particles have different physicochemical behavior. A staged treatment train is therefore more defensible than a one-step prescription.

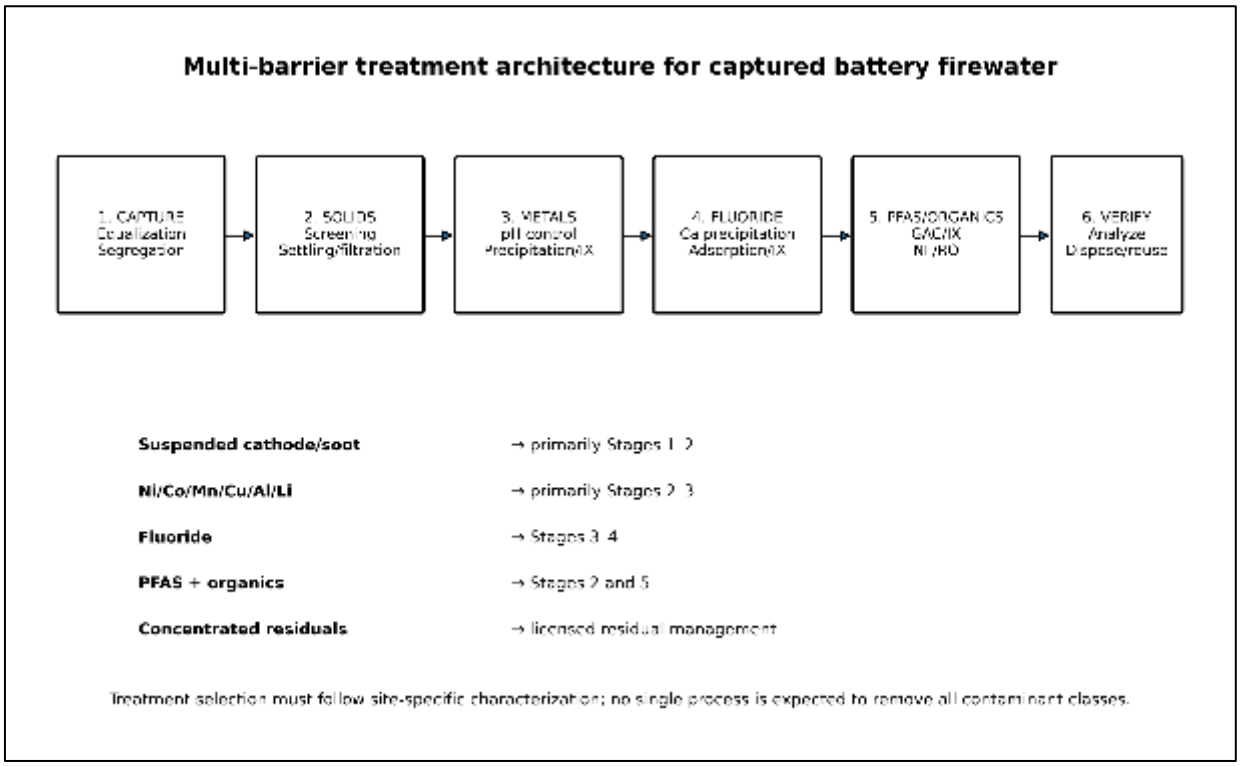

Figure 3: Original contaminant-oriented multi-barrier treatment architecture for captured battery firewater.

Stage 1 should remove debris and suspended solids by screening, settling and filtration. Coagulation/flocculation may be appropriate when fine soot and cathode particles remain dispersed. Stage 2–3 processes can then target dissolved metals. Modern wastewater reviews identify precipitation, adsorption, ion exchange, membrane separation and hybrid processes among the principal metal-removal approaches [20,24]. Chemical precipitation is attractive for concentrated mixed-metal water but creates a sludge that must itself be characterized and managed.

Fluoride requires separate attention because the concentration range may span modest fireground runoff to much stronger long-contact leachate. Recent reviews identify calcium-based precipitation/coagulation, adsorption, ion exchange, electrochemical processes and membranes as viable defluoridation approaches depending on concentration and matrix [21,29]. At high fluoride loading, bulk precipitation followed by a polishing step may be more practical than attempting to use an adsorbent as the sole barrier.

PFAS generally requires a different polishing strategy. Reviews consistently identify granular activated carbon (GAC), specialized ion-exchange media, nanofiltration and reverse osmosis as important separation technologies, while destructive methods remain more challenging at full scale [22,23,26,27,30]. Activated-carbon performance varies with PFAS chain length, dissolved organic matter and competing solutes; a 2024 review emphasizes media regeneration and the reduced performance typically observed for short-chain PFAS [26]. Full-scale technology assessments similarly

caution that treatment success depends on water matrix, residual management, energy use and scalability [27]. Drinking-water experience shows that effective PFAS control often requires concentration of the contaminant into a smaller residual stream rather than simple disappearance [28]. A 2025 municipal-wastewater column study further illustrates the cost and breakthrough implications of GAC polishing [36], while hydrothermal alkaline regeneration research shows that spent GAC can potentially be regenerated while preserving useful long-chain PFAS adsorption capacity [37]. General firewater studies outside the battery domain also demonstrate that PFAS can be transported through contaminated surface-water runoff after major fires [38], reinforcing the need to distinguish battery-derived fluorinated contamination from other fire-scene sources. Reviews of spent-media management and activated-carbon structure–adsorption relationships provide additional support for treating PFAS residuals as a lifecycle problem rather than merely a water-polishing problem [39,40]. The stringent U.S. drinking-water regulation for selected PFAS further underscores the value of preventing uncontrolled transfer of firewater to water-supply sources [31].

The treatment objective should therefore be mass management as well as water polishing. Concentrating PFAS on carbon or ion-exchange resin, precipitating metals into sludge or rejecting contaminants into a reverse-osmosis concentrate creates secondary waste streams that require a secure destination. For this reason, treatment planning should begin with the final residual-management route rather than treating residuals as an afterthought.

6.5 C5 - Confirm

Treatment is complete only when analytical verification supports the selected release, reuse or disposal route. The confirmation panel should be based on the initial characterization and applicable local requirements, not on a fixed universal list. At minimum, major incidents should document the original captured volume, sampling locations and dates, analytical methods, treatment steps, residual quantities, final analytical results and final destination. This chain of custody turns a transient emergency activity into auditable environmental management.

7 DESIGN AND STANDARDS IMPLICATIONS

Battery fire standards have matured rapidly around thermal propagation, explosion and installation protection. NFPA 855 is the principal U.S. standard for stationary energy-storage-system installation and the 2026 edition addresses electrochemical ESS safety at the installation level [34]. UL 9540A provides a standardized method for evaluating thermal runaway and fire propagation; the active 2026 edition focuses on fire and explosion hazard characteristics that inform installation and protection design [35]. These standards are essential, but environmental wastewater characterization is not yet developed to the same level of standardization as heat release, gas generation or propagation.

That asymmetry creates an opportunity for a Battery Firewater Reporting Minimum (BFRM). Future large-scale experiments should report battery chemistry, nominal energy, state of charge, fire initiation method, fraction of the battery involved, suppression agent, water flow and total volume, runoff collection fraction, sampling times, filtered/unfiltered status, pH, conductivity, fluoride, lithium, cathode metals, copper, aluminum, suspended solids, PFAS where warranted and at least one broad organic indicator. For high-consequence testing, an acute aquatic toxicity endpoint should be considered.

Normalization is equally important: dilution can reduce mg/L while total transported mass increases. Future studies should therefore report both concentration and, where feasible, recovered contaminant mass normalized to battery energy, together with a mass balance across air, soot, firewater, residual solids and remaining battery material.

Facility design can apply these principles before an incident. BESS sites should consider emergency drainage isolation, retention volume, safe sampling access, segregation of contaminated and uncontaminated drainage, and pre-incident contracts with environmental laboratories and industrial wastewater contractors. EV parking structures and charging depots can similarly identify drain-isolation points and collection zones. Waste facilities deserve particular attention because hidden batteries can enter mixed waste streams and create complex fires in places that were not designed as battery-storage facilities [8].

8 CONTAMINANT-TO-CONTROL DECISION MATRIX

Table 2: Contaminant-oriented management matrix. Treatment selection must be validated by site-specific treatability testing for major incidents.

Contaminant / property	Why it matters	Early control	Treatment candidates	Verification focus
Soot / cathode particles	Carry metals and organics; foul downstream units	Keep runoff contained; avoid unnecessary resuspension	Settling, filtration, coagulation/flocculation	TSS/turbidity; filtered vs unfiltered metals
Ni, Co, Mn, Cu, Al	Aquatic toxicity and regulatory relevance; chemistry-dependent fingerprint	Prevent drain discharge	pH-controlled precipitation, coagulation, ion exchange, membranes	Dissolved and total metals
Lithium	Highly soluble; can become very concentrated during immersion	Limit unnecessary long-duration water contact	Membrane/ion-exchange or specialized recovery depending concentration	Li concentration and residual stream
Fluoride	Battery-specific; can reach high levels in long-contact water	Capture flushing/immersion water	Calcium precipitation, adsorption, ion exchange, membranes	F^- and pH
PFAS	Persistent; difficult short-chain removal; residual-management challenge	Control soot wash-off and mixed runoff	GAC, specialized IX, NF/RO; destructive options for concentrates	Target PFAS panel + residual destination
Mixed organics / electrolyte products	May contribute toxicity and COD; composition varies by incident	Segregate contaminated runoff from clean stormwater	Adsorption, advanced oxidation where justified, membranes	TOC/COD and targeted organics when indicated

9 PRIORITY RESEARCH AGENDA

The evidence base has moved from proof of possibility to proof of relevance, but it is still too small for universal engineering thresholds. Six research priorities are particularly important.

- **Chemistry-specific fingerprints.** Extend liquid-phase studies beyond NMC to LFP, NCA, lithium-titanate, sodium-ion and emerging solid-state systems.
- **Time-resolved leaching.** Quantify early-hour, multi-day and multi-week release kinetics for intact, vented and fully burned modules.
- **Mass balance.** Experiments should quantify where battery metals, fluorine and persistent organics go across gas, particulate, liquid and solid phases. This would reveal whether a suppression method reduces total environmental release or merely changes the phase.
- **Authentic-firewater treatment trials.** Use real or realistically synthesized mixed firewater because soot, competing ions and organics can alter treatment performance.
- **Field baselines and rapid monitoring.** Establish pre-incident soil/water baselines at sensitive BESS sites and deploy rapid high-density sampling after incidents [12].
- **Operational validation of C5.** Test whether C5 improves containment, sampling completeness and decision quality without delaying fire control.

9.1 Limitations

Direct battery-firewater studies remain limited and heterogeneous in chemistry, fire trigger, suppression method and water volume; universal concentration thresholds are therefore not justified.

C5 and B0–B3 are evidence-informed decision tools, not validated regulatory instruments. Applicable discharge, waste and worker-protection rules take precedence.

PFAS source attribution can be difficult at complex fire scenes, and changing battery chemistries will alter contaminant profiles. This favors contaminant-class and source–pathway–receptor approaches over chemistry-specific assumptions.

10 CONCLUSION

Lithium-ion battery fires create an environmental management problem that extends beyond flame, heat and smoke. Water remains an essential and often highly effective method for cooling batteries and limiting propagation, but once it contacts damaged cells, soot, combustion products or deposited battery material it can become a chemically complex wastewater.

Experimental evidence now demonstrates fluoride, lithium, nickel, cobalt, manganese, copper, aluminum, organics and PFAS in battery-related firewater, while ecotoxicity studies show that the resulting mixtures can produce substantial biological effects. Large-scale BESS testing and real-world post-fire field studies confirm that the problem is not confined to small laboratory cells. Long-duration immersion introduces an additional leaching pathway that should be managed separately from immediate firefighting runoff.

The central policy implication is not to avoid necessary water application; it is to incorporate water containment and disposition into battery-fire planning. The C5 sequence—Contain, Characterize, Classify, Clean and Confirm—provides a practical structure for doing so. Coupled with the B0–B3 triage scheme, source–pathway–receptor model and multi-barrier treatment architecture, it converts contaminated firewater from an improvised cleanup issue into a pre-planned element of battery safety. The next generation of battery-fire standards should evaluate not only whether thermal runaway is controlled, but also where battery-derived contaminants go after control is achieved.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no financial or non-financial conflict of interest related to this review.

Data availability

No new experimental dataset was generated. All quantitative evidence discussed in this study is traceable to the cited publications and public technical resources.

Author contributions

- **Prudvi Saisaran Ponduru:** Conceptualization, Methodology, Investigation, Data Curation, Visualization, Writing - Original Draft, Writing - Review & Editing, Project Administration.
- **Pavani Priya Vyshnavi Nandanavanam:** Investigation, Formal Analysis, Validation, Writing - Review & Editing.
- **Sai Kesav Kumar Ponduru:** Investigation, Validation, Formal Analysis, Visualization, Writing - Review & Editing.

All authors have read and approved the final manuscript.

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