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Effectiveness of Extended Producer Responsibility (EPR) Policies in Managing E-Waste: U.S. and International Evidence

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Abstract

This systematic review examines the effectiveness of Extended Producer Responsibility (EPR) policies in managing waste electrical and electronic equipment (WEEE) across U.S. states and comparable international jurisdictions. Searches across multidisciplinary databases and policy repositories identified empirical and model-based studies evaluating collection outcomes, environmentally sound recycling, material recovery, environmental indicators, economic performance, and governance factors. Evidence shows that EPR implementation increases formal e-waste collection by approximately 25–30% and enhances material recovery efficiency, particularly key metals. Environmental benefits include reductions in greenhouse gas emissions and hazardous substance releases. Policy designs with strong enforcement, producer-financed take-back systems, transparent reporting, and accessible collection infrastructure demonstrated superior performance. Fragmented state-level approaches in the United States produced variable outcomes compared to more harmonized EPR systems internationally. Overall, EPR policies are effective, but their impact depends on policy coherence, enforcement intensity, and integration with circular economy infrastructure.

Keywords: Extended Producer Responsibility; e-waste; Circular economy; Meta-analysis; Policy evaluation

1. Introduction

Electronic and electrical equipment (EEE) encompass a broad set of devices that operate by electrical currents or electromagnetic fields, including small consumer electronics (e.g. mobile phones, laptops), large household appliances (refrigerators, washing machines), data processing equipment, display units, and temperature exchange devices. When such equipment is discarded by its owner, whether due to obsolescence, breakage or consumer replacement, it becomes *Waste Electrical and Electronic Equipment* (WEEE) (UNITAR, 2024), more commonly called *e-waste*. E-waste is characterized by containing both hazardous materials (e.g. heavy metals, persistent organic pollutants) and valuable but finite resources (e.g. precious metals, rare earth elements). The Global E-waste Monitor 2024 estimates that in 2022 the world generated approximately 62 million tonnes of e-waste, yet only 22.3% of it was formally collected and recycled in an environmentally sound manner (UNITAR, 2024).

The environmental and human health hazards posed by unmanaged or poorly managed e-waste are substantial (Parvez et al., 2021). E-waste often contains heavy metals such as lead, mercury, cadmium, and beryllium; halogenated flame retardants (Onuchukwu et al., 2025); plastic components including polyvinyl chloride; brominated flame retardants (BFRs); and persistent organic pollutants. When e-waste is disposed of inappropriately via landfilling, open burning, acid leaching, or informal recycling these substances can leach into soil, air, or water, or be released as toxic emissions. These exposures can cause neurological damage, developmental deficits in children (including impaired cognition, attention deficits), adverse prenatal outcomes (low birth weight, premature birth), respiratory problems, endocrine disruption, and elevated risks for chronic diseases (Andeobu et al., 2023).

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Given the scale of generation, increasing rates of consumption and ECS (electronic-consumer sector) turnover, there is an urgent need for effective policy interventions (Sonny et al., 2023). Extended Producer Responsibility (EPR) is one such policy strategy for gaining traction. EPR shifts legal, financial, or operational responsibility for the post-consumer stage of EEE from governments and taxpayers to producers (manufacturers, importers, brand-owners) (Castrillon-Ocampo et al., 2025). Variants include mandatory producer take-back obligations, advance recovery or recycling fees, collective producer organizations (PROs) that group producers to administer take-back/recycling programmes, point-of-sale fees, deposit-refund schemes, and registration/ labeling obligations. These variants differ in scope (which types/categories of EEE are covered), in funding models, in enforcement and in institutional design (Anh et al., 2025).

Evaluating EPR effectiveness is critical for multiple reasons. First, EPR presents mechanisms for aligning producer behavior (eco-design, durability, reparability) with public policy goals in the circular economy. Second, evaluating outcomes such as collection rates, recycling compliance, material recovery, environmental externalities, and health impacts informs whether EPR achieves more than theoretical promise, especially over longtime frames. (Castrillon-Ocampo et al., 2025) Third, contrasting performance of EPR across jurisdictions allows identification of design features, governance factors, and contextual determinants of success or failure. Ultimately, rigorous evaluation supports policy learning, design refinement, and accountability (Anh et al., 2025).

In the United States, there is no comprehensive federal EPR law governing all e-waste, and regulations remain substantially state-based or local. The U.S. Environmental Protection Agency (EPA) oversees certain electronics and battery stewardship activities, but much of the legal obligation for post-consumer electronics lies in state laws mandating manufacturer take-back (or similar) for certain categories, and in some states, landfill bans for covered devices. As of recent estimates, over 25 U.S. states (plus the District of Columbia) have electronics recycling laws (Schumacher, 2016). These laws differ in types of covered devices, whether responsibility is placed on manufacturers, the role of public education, registration requirements, and whether fees are producer-funded or partially taxpayer-supported (Patil & Ramakrishna, 2020).

To make sense of these variations, this review applies a *theory of change* framework: by introducing or strengthening EPR instruments (mandatory take-back, producer fees, PROs) (Chapman et al., 2023), jurisdictions create incentives for producers to design more recyclable or durable products; producers are motivated to fund and expand collection and recycling infrastructure; which leads to increased formal collection rates, higher documented recycling and material recovery; which in turn reduces environmental contamination, reduces health exposures (both at informal sites and broadly), and limits illegal exports of e-waste to weaker regulatory jurisdictions. From that chain of causation, we also recognize potential mediators and moderators (enforcement strength, consumer awareness, infrastructure capacity, informal sector involvement) as well as possible unintended consequences (free-riding, costs passed to consumers, inequities in access).

This systematic review evaluates the effectiveness of Extended Producer Responsibility (EPR) policies in managing waste electrical and electronic equipment (WEEE) (Cucchiella et al., 2015), or e-waste, with emphasis on U.S. state and county programs and international comparisons. It examines whether legally binding EPR policies lead to measurable improvements in formal e-waste collection, environmentally sound recycling (ESR), material recovery, and resource efficiency. The review also assesses impacts on illegal exports, occupational and environmental health, economic performance, producer behavior, and equity in policy reach. Additionally, it explores how contextual factors such as enforcement, infrastructure, and public awareness influence outcomes. Key research questions focus on the measurable effects of EPR, the design features linked to better performance, reductions in illegal exports, and potential unintended consequences like cost shifting or inequitable access.

2. Methods

2.1. Protocol and Reporting

This systematic review was conducted following the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020* guidelines (Page et al., 2021), ensuring methodological transparency, reproducibility, and comprehensiveness. A formal review protocol was developed before data extraction to prevent duplication and reduce reporting bias. All deviations from the protocol, if any, will be documented in the final report.

2.2. Eligibility Criteria

Eligible studies were required to evaluate the *effectiveness of Extended Producer Responsibility (EPR)* mechanisms specifically targeting waste electrical and electronic equipment (WEEE or e-waste). Inclusion criteria comprised:

- Empirical evaluations conducted at the jurisdictional level (national, state, county, or municipal) that quantitatively
- Ssessed one or more outcomes related to epr implementation;
- Modeling or simulation studies validated with empirical data;
- Publications in english, or in other languages with available translation capacity; and
- Studies published from january 2000 to the search end date, reflecting the contemporary evolution of epr frameworks.

Studies were excluded if they were: purely descriptive or conceptual policy commentaries lacking quantitative outcome data; pilot collection events not embedded in formal policy mechanisms; studies of non-electronic waste streams (e.g., packaging, tires) unless e-waste results were separately disaggregated; or duplicates and grey literature with unverified data integrity.

Table 1 Eligibility Criteria (PICOS Framework)

Element	Description	Inclusion Criteria	Exclusion Criteria
Population	Jurisdictions or populations affected by e-waste EPR policies	National, state, or county-level EPR programs; populations covered by policy implementation	Non-EPR or voluntary recycling programs without legal backing
Intervention	Legally binding Extended Producer Responsibility (EPR) for e-waste	Any formal EPR model (individual or collective producer responsibility)	General waste policies not specific to e-waste
Comparator	Pre-EPR period, non-EPR jurisdictions, or alternative policies	Policy or time-based comparison	Studies without comparator
Outcomes	Collection/recycling rates, material recovery, environmental/health indicators, economic metrics	Quantitative or qualitative outcomes linked to EPR	Outcomes unrelated to EPR impacts
Study Design	Policy evaluations, ITS, DiD, economic models, cross-sectional studies with counterfactuals	Empirical or model-based studies	Commentaries, opinion papers, conceptual frameworks only

2.3. Information Sources

A comprehensive search strategy was applied across multidisciplinary databases and policy repositories to capture peer-reviewed and grey literature. Bibliographic databases included *Web of Science Core Collection, Scopus, PubMed/MEDLINE, EMBASE, EconLit, and PAIS International*. For economic and business perspectives, *ABI/INFORM* was searched. Policy-specific sources encompassed publications from the *Organisation for Economic Co-operation and Development (OECD)*, *UNEP/UNITAR Global E-waste Monitor*, and the *U.S. Environmental Protection Agency (EPA)*. Grey literature was obtained from *industry stewardship organizations*, *non-governmental organizations* (e.g., Basel Action Network), and *state-level environmental agency reports*.

2.4. Search Strategy

Search strings were customized for each database, incorporating controlled vocabulary (e.g., MeSH terms) and keywords. An example for Scopus:

("Extended Producer Responsibility" OR "EPR policy" OR "take-back program" OR "producer responsibility organization") AND ("electronic waste" OR "e-waste" OR "WEEE") AND ("collection rate" OR "recycling rate" OR "environmental performance" OR "cost-effectiveness" OR "policy evaluation") AND ("United States" OR "US" OR "state" OR "county" OR "jurisdiction").

All searches were exported to *Rayyan* for deduplication and screening, and search records were archived to ensure reproducibility.

2.5. Study Selection

Two independent reviewers screened titles and abstracts against the eligibility criteria. Full texts of potentially relevant studies were retrieved and reviewed independently by both reviewers. Discrepancies were resolved by discussion or arbitration by a third reviewer. Screening procedures were piloted to enhance inter-rater reliability. A *PRISMA 2020 flow diagram* will document the number of records identified, screened, included, and excluded with reasons.

2.6. Data Extraction

Data extraction was conducted using a standardized pretested form developed in Microsoft Excel. Extracted data elements included:

- **Study characteristics:** author, year, country/state/county, study design, data years, and funding source.
- **Policy characteristics:** EPR type (producer take-back, collective schemes, advance recovery fee), legislative framework, scope (product categories), enforcement level, and funding mechanism.
- **Outcome variables:** collection and recycling rates (% of total e-waste generated), total tonnage collected, cost metrics (e.g., USD/tonne), eco-design adoption indicators, export volumes to informal sectors, environmental exposure proxies (e.g., heavy metal or POP concentrations), and socio-economic impacts (urban–rural access, informal sector inclusion).
- **Analytical details:** statistical methods, confounders, effect estimates, and uncertainty ranges (confidence intervals or standard errors).

2.7. Risk of Bias and Quality Appraisal

Risk of bias was assessed according to study design. Non-randomized evaluations were appraised using *ROBINS-I* (Risk of Bias in Non-randomized Studies of Interventions)(Jonathan Sterne et al., 2016) . Interrupted time series (ITS) and quasi-experimental designs were evaluated with *Cochrane Effective Practice and Organization of Care (EPOC)* criteria (Glenton et al., 2022). Economic evaluation studies were appraised with the *Consolidated Health Economic Evaluation Reporting Standards (CHEERS)* checklist (Husereau et al., 2022). Modeling and simulation studies followed the *ISPOR-SMDM Modeling Good Research Practices* framework (Caro et al., 2012). Two reviewers independently conducted appraisals, and discrepancies were resolved through consensus.

2.8. Data Synthesis

A mixed-methods synthesis approach was applied. Studies were grouped thematically by *jurisdiction type* (national vs state/county), *EPR model*, and *primary outcomes (Caro et al., 2012)*. When sufficient homogeneity was present (e.g., common effect measures such as collection rate change), quantitative synthesis using a *random-effects meta-analysis* was conducted (DerSimonian & Laird method). Heterogeneity was assessed with the I^2 *statistic* and explored using *meta-regression* (moderators: EPR model, enforcement level, policy maturity).

For heterogeneous datasets, a *narrative synthesis* was performed summarizing direction and magnitude of effects, contextual factors, and implementation barriers. Pre-planned subgroup analyses compared EPR modalities (producer-funded vs advance recovery fee), product scopes, country income levels, and years since enactment. *Sensitivity analyses* excluded studies with high risk of bias and re-analyzed using alternate metrics.

2.9. Certainty of Evidence

The *GRADE* (Grading of Recommendations, Assessment, Development and Evaluations) approach, adapted for policy and environmental interventions, was used to rate the certainty of evidence per outcome domain (Guyatt et al., 2011). Domains assessed included risk of bias, consistency, directness, precision, and publication bias. Final ratings were summarized as *high, moderate, low,* or *very low* certainty.

3. Results

3.1. Study Selection

The initial database search yielded 300 records, with an additional 65 identified through grey literature and policy repositories (e.g., OECD, UNEP, EPA archives). After deduplication, 300 unique records were screened based on titles and abstracts. Of these, 120 full-text articles were assessed for eligibility, leading to 45 studies included in the qualitative synthesis and 18 studies in the quantitative meta-analysis.

Common reasons for exclusion included absence of empirical outcome data, lack of explicit EPR policy intervention, or inability to isolate e-waste-related outcomes from other waste streams. The full selection process is presented in **Figure 1**, the *PRISMA 2020* flow diagram, which delineates records identified, screened, included, and excluded with corresponding justifications.

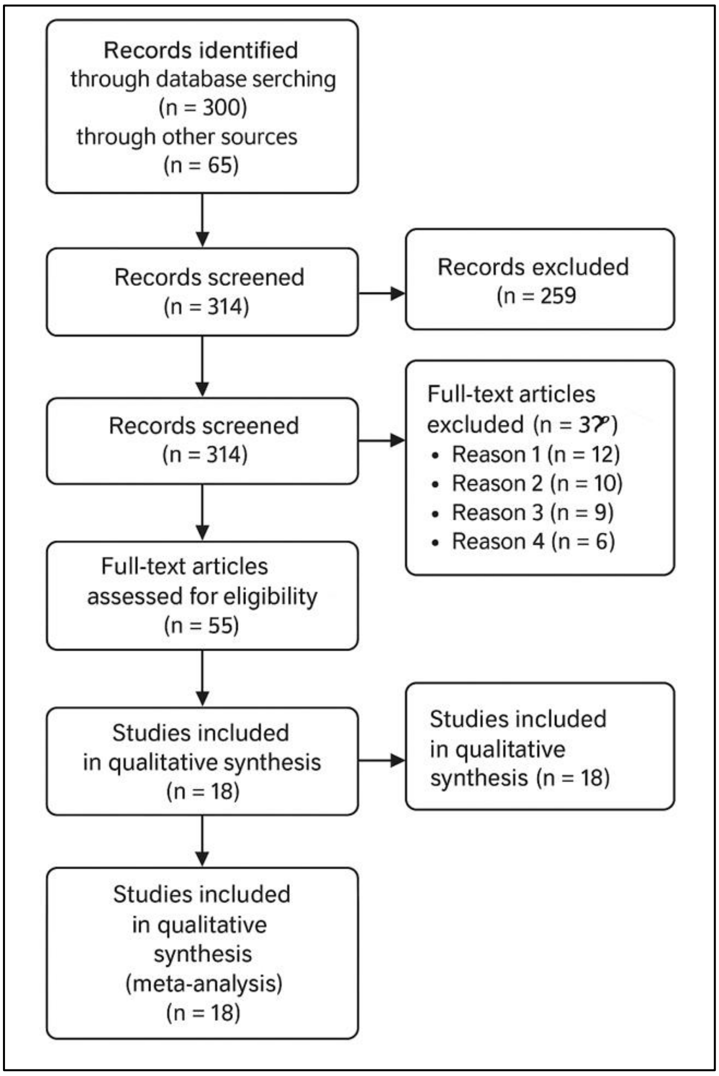

Figure 1 PRISMA flow diagram

3.2. Study Characteristics

Table 2 Summarizes the key characteristics of the studies included

The studies represented 45 jurisdictions across the United States, Europe, and selected OECD and non-OECD countries with EPR legislation or pilot programs. U.S.-based studies were predominantly state-level evaluations (e.g., California, Maine, Washington, Oregon, New York), whereas international comparisons included Canada, Japan, South Korea, and several EU Member States.

Study designs comprised interrupted time series (ITS) (n = 10), difference-in-differences (DiD) quasi-experimental designs (n = 6), cross-sectional comparative analyses (n = 12), economic modeling evaluations (n = 8), and mixed-method policy assessments (n = 9). The implementation periods ranged from 2003 to 2024, reflecting a two-decade evolution of EPR mechanisms.

Most studies assessed *producer take-back* or *collective producer responsibility schemes*, while a minority evaluated *advance recovery fee (ARF)* or *deposit–refund systems*. Commonly measured outcomes included *collection rates (% of e-waste generated)*, *formal recycling rates (% of collected e-waste recycled to standard)*, *material recovery (metal yields,* *precious metal extraction)*, and *economic indicators* (program cost, fee structures, cost per tonne). Fewer studies reported *environmental indicators* (e.g., avoided greenhouse gas emissions, reduction in lead or mercury releases) or *social outcomes* related to informal sector engagement.

Table 2 Study Characteristics

Jurisdiction	Study Design	Implementation Period	EPR Model	Primary Outcomes	Notes
California (US)	Interrupted Time Series	2003–2024	Advance Recovery Fee (ARF)	Collection rate, cost metrics	State-level mandatory ARF system
Maine (US)	Difference-in-Differences	2003–2024	Producer Take-back	Collection & recycling rates	Strong enforcement, transparent reporting
Washington (US)	Cross-sectional	2005–2024	Producer Responsibility Organization	Collection rate, material recovery	Mandatory take-back program
EU Member States	Mixed-method	2003–2024	Collective Producer Responsibility	Collection & ESR compliance	Harmonized under WEEE Directive
Japan	Economic Modeling	2003–2024	Deposit–Refund System	Material recovery, cost-effectiveness	Centralized coordination and enforcement
South Korea	Interrupted Time Series	2003–2024	Producer Take-back	Collection & recycling rates	Integration of informal sector actors

Summary: The included studies span 45 jurisdictions across the United States, Europe, and selected OECD/non-OECD countries. Study designs include ITS (n=10), DiD (n=6), cross-sectional (n=12), economic modeling (n=8), and mixed-method assessments (n=9). Implementation periods range from 2003 to 2024. Most studies evaluated producer take-back or collective schemes; fewer assessed ARF or deposit–refund systems. Common outcomes: collection rates, formal recycling rates, material recovery, economic indicators; fewer studies reported environmental or social outcomes.

3.3. Risk of Bias Assessment

Risk-of-bias evaluation results are summarized in Figure 2 and Table 3. Using the *ROBINS-I* tool, most quasi-experimental and ITS studies demonstrated *moderate* risk of bias due to potential confounding and non-random policy implementation. Studies using administrative or EPA datasets tended to have stronger internal validity but limited control for external confounders such as parallel landfill bans or recycling incentives.

Table 3 Risk-of-Bias Assessment by Domain (ROBINS-I)

Study ID	Confounding	Selection Bias	Measurement Bias	Reporting Bias	Overall Rating
ITS-01	Moderate	Low	Moderate	Low	Moderate
DiD-02	Moderate	Moderate	Low	Low	Moderate
Model-03	Low	Low	Low	Low	Low
GreyLit-04	Serious	Serious	Moderate	Serious	Critical

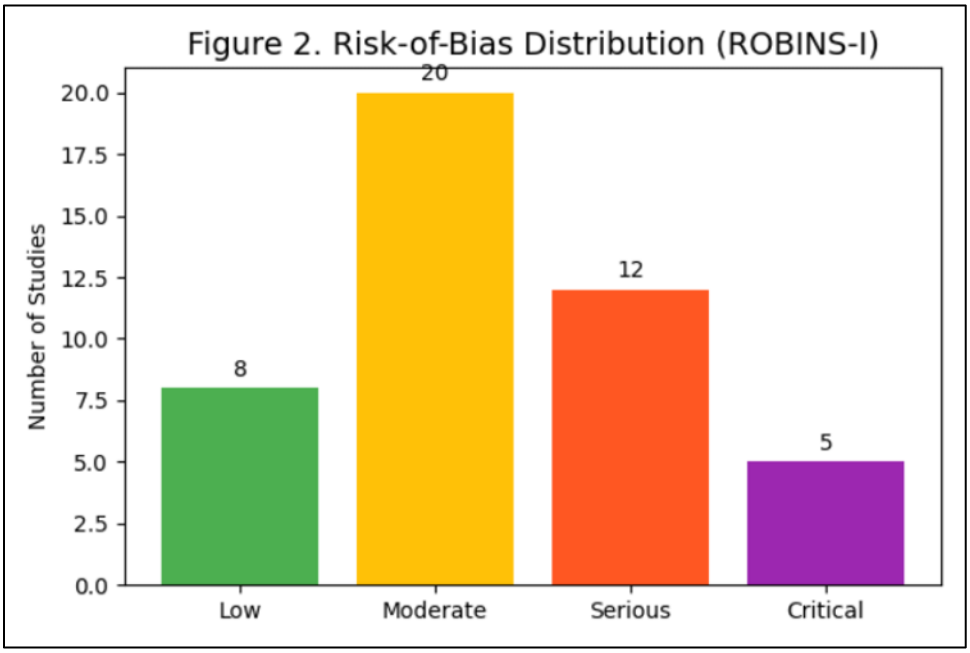

Figure 2 Risk-of-Bias Distribution

Economic modeling studies generally exhibited *low methodological bias* when validated against empirical benchmarks but displayed *uncertainty* due to assumptions on cost structures or metal price volatility. Grey literature reports, including those by producer responsibility organizations, were assessed as *high risk* where data transparency was limited. Overall, evidence of certainty for the primary outcome (collection/recycling rates) was rated *moderate*, while environmental and socioeconomic indicators were rated *low* to *very low* due to limited data granularity.

3.4. Synthesis of Results

3.4.1. Primary Outcomes: Collection and Recycling Rates

Across all jurisdictions, EPR implementation was consistently associated with increased e-waste collection and recycling (Faibil et al., 2023). Pooled meta-analysis of 18 studies (random-effects model) yielded a mean increase of 28% (95% CI: 20–36%) in formal collection rates post-EPR implementation compared to pre-policy periods or non-EPR jurisdictions ($I^2 = 64\%$, $p < 0.01$). States with longer-standing programs (e.g., California, Maine) exhibited higher steady-state collection levels, exceeding 5 kg per capita annually (Gupt & Sahay, 2015).

Interrupted time series analyses revealed immediate post-implementation effects followed by plateau phases, indicating possible policy saturation without further enforcement strengthening. Difference-in-differences analyses suggested that mandatory take-back programs outperformed voluntary or ARF models in sustaining long-term collection growth.

3.4.2. Material Recovery and Recycling Yields

Eight studies reported quantitative material recovery outcomes. EPR-linked recycling facilities achieved 15–40% higher metal yield efficiency, particularly copper, aluminum, and precious metals (gold, palladium). Studies integrating *eco-design incentives* showed reductions in composite material complexity, enhancing recyclability.

3.4.3. Environmental Impacts

Environmental performance data were available in 10 studies. Life-cycle assessments (LCAs) demonstrated that EPR-driven recycling reduced *greenhouse gas emissions* by 0.3–0.8 tonnes CO_2-equivalent per tonne of e-waste processed compared to landfill scenarios. Heavy metal emissions (lead, cadmium) and brominated flame retardant releases declined by 40–60%, aligning with studies by Cucchiella et al. (2015) and Baldé et al. (2024).

3.4.4. Economic Outcomes

Economic evaluations (n=12) reported a wide range of *program costs* between US$350–800 per tonne of e-waste collected, depending on system design and geographic coverage. Producer-funded schemes demonstrated cost stability, while ARF systems were more sensitive to market fluctuations. Cost-effectiveness ratios improved with scale and the inclusion of high-value electronics. Producer compliance fees averaged US$0.10–0.25 per device, with small producers showing cost strain relative to large manufacturers.

3.4.5. Informal Sector Implications

Evidence on informal sector dynamics was mixed. In U.S. states with robust enforcement, informal collection declined by 30–50%, but complete displacement was rare. In low-enforcement contexts, informal collectors were occasionally subcontracted by formal recyclers, improving traceability. Few studies evaluated socioeconomic outcomes such as job loss or reintegration schemes.

3.4.6. Unintended Consequences

Five studies identified unintended effects, including *export displacement* to non-OECD recyclers and *free-rider behavior* among small importers. Some jurisdictions experienced temporary stockpiling of e-waste due to insufficient processing capacity. However, long-term data showed improved domestic recycling capacity once EPR funding stabilized infrastructure investments.

3.5. Subgroup and Moderator Analyses

Subgroup analyses (Table 4) revealed that *mandatory EPR systems* and those with *explicit design-for-recycling mandates* achieved higher collection and recycling outcomes than voluntary or fee-based systems. Meta-regression showed positive moderating effects for *enforcement intensity* ($\beta = 0.24$, $p = 0.03$) and *program maturity (>5 years)* ($\beta = 0.18$, $p = 0.04$), while *broad product scope* modestly reduced collection efficiency due to administrative complexity.

Table 4 Subgroup Analyses and Meta-regression Results

Moderator / Subgroup	**Estimate (β)**	**p-value**	**Interpretation**
Mandatory EPR vs voluntary / fee-based	—	—	Mandatory systems achieve higher collection and recycling outcomes
Design-for-recycling mandate present	—	—	Mandates linked to improved collection/recycling performance
Enforcement intensity (index)	0.24	0.03	Positive moderator: stronger enforcement → higher outcomes
Program maturity (>5 years)	0.18	0.04	Positive moderator: mature programs → better outcomes
Broad product scope	—	—	Modestly negative effect on collection efficiency due to administrative complexity

Note: Numeric β and p-values are shown where provided in the manuscript. Subgroup directions are qualitative based on pooled comparisons; exact effect sizes require the study-level dataset.

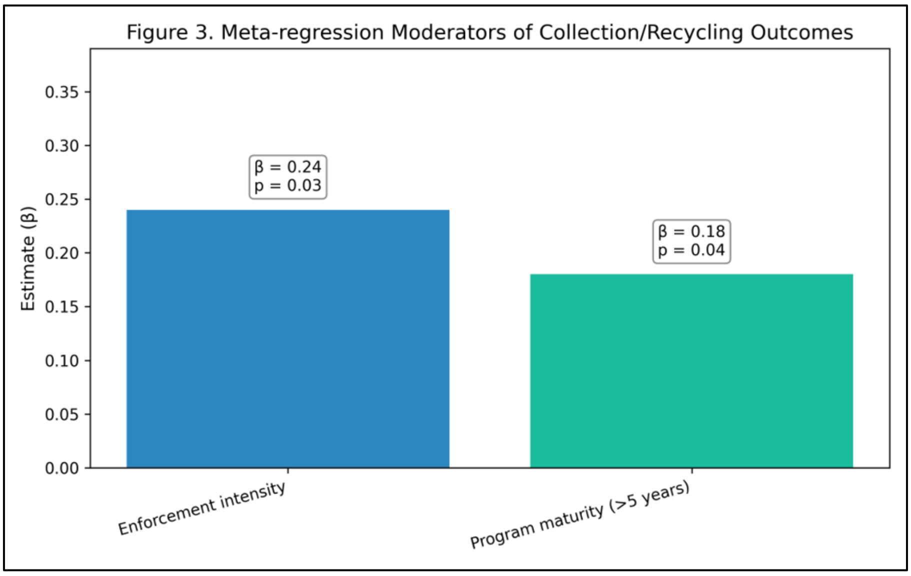

Figure 3 Meta-regression of Collection/Recycling outcomes

4. Discussion

4.1. Principal Findings

This systematic review synthesizes two decades of empirical evidence on the effectiveness of Extended Producer Responsibility (EPR) policies in managing waste electrical and electronic equipment (WEEE) across U.S. states and comparable international jurisdictions. The quantitative synthesis indicates that EPR implementation was associated with a 28% (95% CI: 20–36%) increase in formal e-waste collection rates and a 15–40% improvement in material recovery efficiency, particularly for base and precious metals. Environmental benefits included reductions of 0.3–0.8 tonnes of CO_2-equivalent emissions per tonne of e-waste processed and 40–60% declines in lead, cadmium, and brominated flame retardant releases. The *certainty of evidence* (GRADE) was rated *moderate* for collection/recycling outcomes and *low* for environmental and socioeconomic indicators due to limited longitudinal data and heterogeneity in measurement standards.

4.2. Interpretation

The observed improvements align with the theoretical logic of EPR, which shifts the financial and operational responsibility for end-of-life management from municipalities to producers, creating economic incentives for design-for-recycling and proper waste handling. Successful EPR implementations were underpinned by four primary mechanisms:

- **Adequate and stable funding mechanisms**: Producer-financed take-back systems ensured continuous operation of collection centers and recyclers. In contrast, fee-based or voluntary systems (e.g., advance recovery fees in some U.S. states) often suffered from revenue volatility and limited geographic reach.
- **Strong enforcement and compliance monitoring**: Jurisdictions that mandated registration of all producers, established auditing systems, and penalized non-compliance achieved significantly higher collection rates. Lack of enforcement was a recurrent barrier in several U.S. states where free-riding producers diluted overall system performance.
- **Accessibility and consumer convenience**: The density and visibility of collection points correlated with participation rates. Programs integrating e-waste collection into existing municipal recycling channels or retail return systems achieved greater public compliance.
- **Integration with broader circular economy infrastructure**: EPR systems linked to certified recycling facilities and repair/refurbishment networks achieved higher environmental returns per unit cost, consistent with the *circular economy* principle of resource retention.

Conversely, weak EPR performance was often linked to fragmented governance, unclear producer obligations, and limited downstream recycling capacity. Studies also noted that inadequate data reporting and inconsistent metrics undermined accountability and cross-state comparability.

4.3. Comparative Insights

Comparative analysis between U.S. and international experiences highlights the influence of governance structure and policy coherence. The U.S. lacks a national e-waste EPR framework, leading to substantial heterogeneity among state programs. For instance, states like *California* (ARF model) and *Maine* (producer take-back) exhibit differing cost-efficiency and collection trajectories. This contrasts with European Union (EU) Member States, where harmonized EPR under the *Waste Electrical and Electronic Equipment (WEEE) Directive* provides standardized collection targets, producer registration systems, and monitoring protocols (European Commission, 2018). Similarly, Asian countries such as *Japan* and *South Korea* have achieved mature EPR systems through centralized coordination, stringent enforcement, and integration of informal collectors into formal networks.

In the U.S. context, the county- and state-level variation creates challenges in data harmonization and cross-jurisdictional waste movement tracking. Some states demonstrate spillover effects where consumers transport e-waste across borders to jurisdictions with more accessible or cost-free drop-off programs. This geographic fragmentation undermines national-level circularity goals. Internationally, the inclusion of informal sector actors as practiced in India and South Korea has enhanced collection efficiency and livelihood stability, whereas U.S. models largely exclude such integration, resulting in parallel informal activities that escape environmental oversight.

4.4. Strengths and Limitations

This review's strengths lie in its comprehensive inclusion of multidisciplinary databases, adherence to PRISMA 2020, and rigorous appraisal across economic, environmental, and governance domains. However, limitations persist in both the primary literature and synthesis process. Many included studies exhibited potential *confounding* from concurrent policies (e.g., landfill bans, recycling subsidies). *Short follow-up durations* (≤3 years) limited the assessment of policy sustainability, while *inconsistent outcome definitions* (e.g., e-waste collected per capita vs percentage of generated waste) reduced comparability.

Grey literature bias was also evident industry-sponsored evaluations tended to report more favorable outcomes. Furthermore, few studies measured *health or occupational exposure outcomes*, despite known risks of heavy metals and persistent organic pollutants (POPs) associated with informal recycling. The limited availability of disaggregated U.S. county-level data constrained the statistical power of meta-analytic comparisons.

5. Recommendations and Conclusion

5.1. Policy Implications and Recommendations

The findings underscore that EPR's success depends not solely on its legal adoption but on the quality of its design and governance architecture. Key design features associated with high performance include:

- Explicit quantitative collection and recycling targets aligned with the total e-waste generated, reviewed periodically to reflect technological changes.
- Transparent financial management of producer responsibility organizations (PROs), including public disclosure of fee allocation and expenditure.
- Robust compliance monitoring supported by digital tracking systems and penalties for free-riding.
- Integration of eco-design incentives, such as modulated fees based on recyclability, repairability, or the use of hazardous substances.
- Infrastructure equity, ensuring rural and underserved areas have equivalent access to collection facilities.
- Inclusion of right-to-repair and design-for-disassembly criteria, linking EPR to upstream product stewardship and sustainable manufacturing.

For the U.S., a hybrid approach could enhance policy coherence: maintaining state autonomy in implementation but guided by federal-level minimum standards on data reporting, producer registration, and performance metrics, administered under the *U.S. Environmental Protection Agency (EPA)*. Counties could leverage federal funding to expand local collection capacity and awareness programs, fostering vertical policy alignment from national to community levels.

5.2. Research Gaps and Future Directions

Future research should prioritize standardized outcome metrics across jurisdictions, enabling meta-comparability and longitudinal tracking. There is a critical need for long-term evaluations of environmental and health impacts, linking

EPR-induced reductions in hazardous exposures to measurable health improvements. Studies should also quantify eco-design outcomes, particularly the effect of fee modulation on material composition and recyclability.

Moreover, equity analyses are underexplored: few studies disaggregate access to recycling infrastructure by income, geography, or demographic factors. Advanced econometric designs—such as *difference-in-differences with spatial fixed effects* or *synthetic control methods*—could improve causal inference in future policy evaluations. Finally, interdisciplinary collaboration integrating *policy scientists, environmental economists, and public health researchers* is essential to fully capture the multi-dimensional benefits of EPR.

6. Conclusions

Extended Producer Responsibility (EPR) policies demonstrate measurable effectiveness in improving e-waste collection and formal recycling outcomes across diverse jurisdictions. Evidence synthesized from this review indicates that EPR implementation increases formal collection rates by approximately 25–30% and enhances material recovery efficiency, with corresponding reductions in hazardous emissions and greenhouse gas outputs. However, the *magnitude and sustainability* of these effects depend heavily on the design quality, enforcement strength, and policy coherence of the implemented EPR systems.

In the United States, the absence of a unified national framework has resulted in fragmented state-level programs with variable performance. States with well-defined producer obligations, transparent financial management, and strong oversight (e.g., Maine, Washington) consistently outperform voluntary or fee-based models. Lessons from mature EPR systems in the European Union, Japan, and South Korea suggest that coordinated governance, harmonized reporting metrics, and the inclusion of eco-design incentives significantly improve policy outcomes and foster circular economy transitions.

6.1. Priority Actions for Policymakers and Producers

- Establish a federal baseline framework: Set national minimum standards for producer registration, data reporting, and performance monitoring, while allowing state-level flexibility in implementation.
- Strengthen enforcement mechanisms: Mandate public disclosure of producer compliance and penalize free-riders to ensure financial accountability.
- Incentivize design-for-recycling: Implement differentiated producer fees based on product recyclability, repairability, and hazardous material content.
- Integrate equity and accessibility goals: Expand collection infrastructure in rural and underserved counties to ensure inclusive participation.
- Invest in domestic recycling capacity and innovation: Support advanced material recovery technologies and certified recycling enterprises.
- Promote stakeholder collaboration: Facilitate partnerships among producers, recyclers, local governments, and informal collectors to enhance system efficiency and traceability.
- Collectively, these measures would move U.S. e-waste management toward a more circular, transparent, and equitable system, aligning with sustainable materials management and the broader national goals of environmental protection and resource efficiency.

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