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Evaluating the Effectiveness of Plastic EPR Systems in Reducing Mismanaged Plastic Waste and Aquatic Pollution

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ABSTRACT

The environmental purpose of Extended Producer Responsibility extends beyond administrative compliance: plastic that escapes the managed waste system enters terrestrial and aquatic environments regardless of whether producer obligations have been discharged. This study tests whether the reporting architecture supporting EPR in India is capable of detecting that escape. Using State-level data from the Central Pollution Control Board's 2021-22 implementation report, mismanaged plastic is computed as the difference between reported generation and reported collection for the eight jurisdictions that report both quantities. The uncollected fraction ranges from 0.00 to 90.56 per cent, with a median of 6.47 per cent and a subtotal of 12.19 per cent once a jurisdiction with an internally contradictory entry is excluded. Four of the eight jurisdictions report collection exactly equal to generation, implying zero mismanaged plastic, which is not a plausible physical outcome and indicates that collection is being recorded as an estimate derived from generation rather than measured independently. Downstream mass balances close for one State, fail by 2.34 per cent for a second, and in a third the reported landfill quantity alone exceeds the State's own reported generation by a factor of 1.19. An EPR Leakage Avoidance Index is specified and reported in bounded form, giving an upper bound of 0.8781 for the subtotal, because no source in the examined corpus supplies the aquatic leakage fraction required to close it. The study concludes that the Indian EPR reporting instrument cannot presently distinguish complete collection from unmeasured collection, and therefore cannot evidence leakage prevention, irrespective of how fully producer obligations are discharged.

Keywords: Extended Producer Responsibility; mismanaged plastic waste; plastic leakage; aquatic pollution; material flow analysis; India

Nomenclature

G plastic waste generated, t yr^{-1}

C plastic waste collected, t yr^{-1}

M mismanaged plastic, t yr^{-1}

L leakage to the environment, t yr^{-1}

L_{aq} leakage to aquatic systems, t yr^{-1}

POM plastic packaging placed on the market, t yr^{-1}

k conversion rate from mismanaged waste to marine debris, dimensionless

P_c coastal population within 50 km of a coast, persons

g per capita waste generation, kg person^{-1} d^{-1}

f_p plastic fraction of waste, dimensionless

f_{mm} mismanaged fraction of waste, dimensionless

ELAI EPR Leakage Avoidance Index, dimensionless

1. Introduction

Extended Producer Responsibility is justified in environmental terms. The instrument exists because plastic packaging that is not recovered imposes costs on ecosystems and on the public bodies that manage waste. Its success condition, stated environmentally rather than administratively, is that less plastic escapes into the environment than would have escaped without it.

Conventional EPR reporting does not measure that condition. It measures obligations set and obligations discharged. Plastic can escape the managed system at many points: waste never collected, losses during transport, residues rejected at sorting, residues generated during recycling, and material consigned to uncontrolled disposal. None of these appears in a recovery figure.

The relationship between recovery and avoided leakage is not proportional. Whether an additional tonne recovered prevents an additional tonne of leakage depends on where that tonne was recovered, what would otherwise have happened to it, and whether the receiving geography drains to an aquatic system. A national recovery rate carries none of that information.

This study asks a prior question. Before asking whether EPR reduces leakage in India, it asks whether the data generated by the EPR and waste-management reporting systems is capable of answering that question at all. The answer determines whether a leakage-avoidance metric can be populated or only specified.

The objectives are to quantify plastic generated and recovered within the available national datasets; to estimate mismanaged plastic and potential leakage using those datasets; to determine the proportion of generated plastic potentially entering aquatic environments; to compare recovery performance against estimated leakage and identify divergence; and to develop an EPR Leakage Avoidance Index linking physical recovery performance with potential environmental leakage prevention.

2. Literature review and research gap

Research on plastic leakage and research on producer responsibility have developed largely in parallel. Leakage studies model the movement of mismanaged waste into rivers, coastal zones and marine systems, typically using national waste-generation estimates and assumed mismanagement fractions. EPR studies examine obligations, institutional arrangements and compliance. The two literatures rarely share a material-flow framework.

Five gaps follow. Existing EPR research rarely integrates producer-responsibility data with quantitative leakage or mismanaged-waste assessments using a common framework. Riverine, freshwater and marine-plastic studies generally examine leakage pathways independently of producer-level obligations and recovery performance. The quantitative relationship between EPR recovery, unmanaged plastic and environmental leakage remains insufficiently established across waste-management systems. Plastic leakage is rarely normalised against plastic generated or plastic placed on the market, which limits comparison between countries with different waste-generation profiles. And no index exists that assesses whether EPR recovery translates into measurable leakage prevention.

A sixth gap, less frequently stated, motivates the present design. The literature generally treats official waste statistics as an input to leakage models rather than as an object of examination. Where the mismanagement fraction is itself derived from those statistics, the reliability of the statistics determines the reliability of every downstream estimate.

3. Materials and methods

This section sets out the data source and its scope, the definition of mismanaged plastic within the material-flow boundary, the criterion by which jurisdictions enter the analysis, the construction of the index, and the verification applied.

3.1 Data source and scope

The analysis uses the Central Pollution Control Board's Annual Report (Interim) 2021-22 on the Implementation of the Plastic Waste Management Rules 2016, prepared under rule 17(4) of those Rules. State-level entries are taken from the report's own narrative sections. The regulatory framework is taken from Schedule II of the Plastic Waste Management Rules as notified on 16 February 2022, reproduced as Annexure III to the Board's Guidelines for Assessment of Environment Compensation of April 2024.

No figure is estimated, interpolated or imported from another jurisdiction. Where a quantity is required and not reported, that is stated.

3.2 Definition of mismanaged plastic

Within the material-flow boundary, mismanaged plastic is the residual of the generation balance:

$$G = C + M \qquad (1)$$

from which

$$M = G - C \qquad (2)$$

Leakage to the environment satisfies

$$0 \leq L \leq M \qquad (3)$$

because mismanaged material may be informally landfilled, openly burned, or retained on land without reaching an aquatic system. M is therefore an upper bound on L, and the two are equal only in the limiting case where no mismanaged plastic is retained on land.

3.3 Inclusion criterion

A jurisdiction enters the analysis only if the source reports both G and C for it. Eight of the 34 reporting States and Union Territories satisfy this condition. Jurisdictions reporting generation alone are excluded rather than assigned an assumed collection rate.

3.4 The EPR Leakage Avoidance Index

The index expresses the share of generated plastic that does not leak:

$$\mathrm{ELAI} = 1 - \frac{L}{G} \qquad (4)$$

bounded on the interval from zero to one, with a normalised variant for cross-jurisdiction comparison in which market placement replaces generation in the denominator:

$$\mathrm{ELAI_n} = 1 - \frac{L}{\mathrm{POM}} \quad (5)$$

Where L is not reported directly, the index is evaluated in bounded form. Substituting the upper bound of equation (3) into equation (4) gives

$$\mathrm{ELAI_{upper}} = 1 - \frac{M}{G} \quad (6)$$

which treats all mismanaged plastic as leakage and therefore returns the least favourable admissible value. The corresponding lower bound, ELAI = 1, treats none of it as leakage.

3.5 The published conversion parameter

Equation (4) can be closed where a value for the conversion rate k from mismanaged waste to aquatic debris is available. Jambeck et al. (2015) estimate national marine plastic inputs from a chain of the form

$$M_c = P_c \times g \times f_p \times f_{mm} \times 365 \qquad (7)$$

for coastal mismanaged plastic, where P_c is the population within 50 km of a coast, g the per capita waste generation rate in kilograms per person per day, f_p the plastic fraction of waste and f_{mm} the mismanaged fraction, with the factor 365 annualising a daily rate. Marine input then follows as

$$L_{aq} = M_c \times k \qquad (8)$$

with the conversion rate bounded by that study as

$$0.15 \leq k \leq 0.40 \quad (9)$$

and a central value of $k = 0.25$. The applicability of this parameter to the Indian jurisdictions available here is examined in section 4.6 rather than assumed.

3.6 Verification

All arithmetic was executed computationally. Each State's reported chain was tested for closure: collection was compared against the sum of its reported destinations, and each reported quantity was compared against the State's own reported generation. Failures to close are reported as results.

4. Results

Results are presented in six parts: the uncollected fraction by jurisdiction, the four reports of zero mismanagement, the internally contradictory Tamil Nadu entry, the downstream mass-balance closure tests, the index in bounded form, and the coverage the analysis achieves.

4.1 Uncollected fraction by jurisdiction

Table 1 gives generation, collection and the derived uncollected quantity for the eight jurisdictions reporting both.

Table 1 – Reported generation, collection and uncollected plastic, 2021-22

State/UT	Generation (TPA)	Collected (TPA)	Uncollected (TPA)	Uncollected (%)
Bihar	53,232.339	46,340.007	6,892.332	12.95
Jharkhand	53,432.966	44,715.945	8,717.021	16.31
Ladakh	1,915.050	1,915.050	0.000	0.00

State/UT	Generation (TPA)	Collected (TPA)	Uncollected (TPA)	Uncollected (%)
Sikkim	104.740	104.740	0.000	0.00
Rajasthan	72,044.771	60,650.191	11,394.580	15.82
Tamil Nadu	397,387.684	37,531.255	359,856.429	90.56
Odisha	40,696.430	40,696.430	0.000	0.00
Tripura	169.630	169.630	0.000	0.00
Subtotal	618,983.610	232,123.248	386,860.362	62.50

The uncollected fraction ranges from 0.00 to 90.56 per cent, a span of 90.56 percentage points, with a median of 6.47 per cent.

4.2 The zero-mismanagement reports

Four of the eight jurisdictions — Ladakh, Sikkim, Odisha and Tripura — report collection exactly equal to generation, implying complete collection and zero mismanaged plastic. The Tripura entry states explicitly that there is 100 per cent collection of plastic waste.

A mismanaged fraction of exactly zero is not a plausible physical outcome for an open waste-management system serving a dispersed population. The more consistent reading is that collection has been recorded as equal to an estimate of generation rather than measured independently. Where C is derived from G, the quantity $G - C$ is definitionally zero and carries no information about collection performance.

This has a consequence that extends beyond the four jurisdictions. The reporting instrument cannot distinguish a State with genuinely complete collection from a State that has estimated collection as equal to generation. Both produce the same entry. No external evidence in the source permits the two to be separated.

4.3 Tamil Nadu: an internally contradictory entry

Tamil Nadu reports generation of 397,387.684 TPA against collection of 37,531.255 TPA, an apparent uncollected fraction of 90.56 per cent. The same entry states that approximately 1.7 lakh tonnes, roughly 170,000 TPA, was channelized for recycling.

Collection cannot be smaller than the quantity channelized for recycling out of that collection. The stated recycling quantity is 4.5 times the stated collection. The entry is internally contradictory and the derived uncollected fraction is an artefact rather than a measurement.

Excluding Tamil Nadu, the remaining seven jurisdictions report generation of 221,595.926 TPA against collection of 194,591.993 TPA, an uncollected fraction of 12.19 per cent. This is the value carried forward.

4.4 Downstream mass-balance closure

Three jurisdictions report collection together with all reported downstream destinations. Table 2 tests closure.

Table 2 – Mass-balance closure test, collection against reported destinations

State	Collected (TPA)	Recycled (TPA)	Reuse (TPA)	Landfill (TPA)	Sum of destinations (TPA)	Residual (TPA)
Bihar	46,340.007	17,101.544	2,878.648	63,474.187	83,454.379	−37,114.372
Jharkhand	44,715.945	29,468.085	598.082	13,605.069	43,671.236	+1,044.709
Sikkim	104.740	73.480	0.500	30.760	104.740	0.000

Sikkim closes exactly. Jharkhand closes to within 1,044.709 TPA, 2.34 per cent of collection, which is consistent with unreported process and transport losses and is the only entry in the set from which a loss term could be inferred.

Bihar does not close under any interpretation. The reported landfill quantity of 63,474.187 TPA exceeds both reported collection, 46,340.007 TPA, and reported generation, 53,232.339 TPA. The three destinations sum to 83,454.379 TPA, which is 1.57 times the State's own reported generation. The residual is negative by 37,114.372 TPA. No physical reading reconciles these four figures as a single year's flows for a single jurisdiction.

4.5 The index in bounded form

Applying equation (6) to the seven-jurisdiction subtotal excluding Tamil Nadu:

$ELAI_{upper} = 1 - (27{,}003.933 \div 221{,}595.926) = 0.8781$

The true value lies between 0.8781 and 1.0000. The width of that interval, 0.1219, is the whole of the uncertainty attributable to the aquatic conversion rate.

4.6 Why the published conversion parameter cannot close the interval

Applying equations (8) and (9) to the usable subtotal would narrow the interval substantially. Table 3 reports that sensitivity.

Table 3 – Leakage sensitivity to the published conversion rate, usable subtotal

Conversion rate *k*	*L*_aq (TPA)	ELAI
0.15, low	4,050.6	0.9817
0.25, central	6,751.0	0.9695
0.40, high	10,801.6	0.9513

These values are reported as a sensitivity and not as an estimate, for a reason that is itself a finding.

The conversion rate *k* in equation (8) is calibrated by Jambeck et al. (2015) on populations living within 50 km of a coast. The three jurisdictions whose reporting permits a mismanaged-plastic calculation in this study are Bihar, Jharkhand and Rajasthan. All three are landlocked. None contains any population within 50 km of a coast, and the parameter's domain of definition therefore excludes every jurisdiction for which the numerator is available.

The Indian jurisdictions whose reporting permits the calculation are precisely those to which the published marine conversion parameter does not apply. The coastal States whose geography the parameter was built for — those with substantial populations within the 50 km band — are absent from the usable subset because they do not report collection in a form permitting *M* to be computed.

The corpus separately contains an estimate of 0.75 million tonnes of plastic entering the ocean annually from the Philippines, attributed to the same 2015 study. Transferring that national result to India would substitute one country's coastal geometry, drainage and settlement pattern for another's, and is not done here.

4.7 Coverage of the analysis

The eight jurisdictions reporting both quantities account for 618,983.610 TPA of the 3,846,936 TPA national generation figure, that is 16.09 per cent. Excluding Tamil Nadu, the usable subtotal covers 221,595.926 TPA, or 5.76 per cent of national generation. The mismanagement analysis that the national reporting instrument supports therefore covers less than one-sixteenth of the plastic waste it reports.

5. Discussion

The discussion considers what the reporting system can and cannot evidence, the asymmetry between the precision of obligation and the silence on outcome, why normalisation matters for comparison, and the implications for regulators, researchers and the instrument itself.

5.1 What the reporting system can and cannot evidence

The instrument reports generation for 34 jurisdictions, processing for 20, and collection in a form permitting a mismanagement calculation for eight, of which one is internally contradictory and four report a definitionally uninformative zero. Three jurisdictions in the entire national dataset yield a usable, non-trivial mismanaged-plastic estimate.

A reporting system in this condition cannot evidence leakage prevention. It cannot show that leakage has fallen, because it does not measure leakage; it cannot show that collection has improved, because collection is in several cases derived from generation rather than measured; and it cannot be aggregated, because the reporting population differs between every quantity.

This is a finding about the instrument, not an accusation against the entities reporting through it. The Plastic Waste Management Rules require States to report under Form VI on an annual cycle, and Form VI as amended requests quantities that several States are evidently not in a position to measure independently. Where a measurement system is absent, an estimate will be entered, and where the estimate for collection is anchored to the estimate for generation, the derived mismanagement figure is zero by construction.

5.2 The asymmetry between obligation and outcome

The EPR architecture is precise about obligation and silent about outcome. Schedule II fixes the obligation as a percentage of a defined eligible quantity, sets category-wise minimum recycling levels by year, provides for certificates, a trading platform with a price band, and environment compensation at a stated rate per tonne. Every one of those quantities is specified to the tonne or the rupee.

Against that, the environmental outcome the instrument exists to secure has no reporting field at all. No provision requires the measurement of leakage, of mismanaged plastic, or of the environmental fate of the fraction that is not recovered. A producer can discharge every obligation precisely and the system will record no information about whether plastic reached a river.

That asymmetry is the structural reason the index cannot be closed. It is not a data-collection failure within a well-specified system; the quantity is not specified.

5.3 Why normalisation matters for comparison

Leakage expressed as an absolute tonnage rewards small countries and penalises large ones. Expressed as a fraction of generation it rewards countries that under-report generation. Expressed as a fraction of plastic placed on the market, as in equation (4), it is less sensitive to waste-estimation practice, because market placement is recorded through commercial channels that exist independently of the waste-management system.

For India the EPR portal records an aggregate obligation that functions as a lower bound on regulated market placement. That quantity is more robustly founded than the generation estimate, being assembled from entity-level returns rather than State-level approximations, and is the preferable denominator for any future leakage normalisation.

5.4 Implications

For regulators, the immediate implication is that collection should be reported as a measured quantity with its measurement basis stated, and that Form VI should distinguish measured from estimated entries. A field recording whether collection was weighed, inferred from vehicle movements, or estimated as a fraction of generation would make the present analysis possible nationally rather than for three jurisdictions.

For researchers using Indian plastic-waste statistics, the implication is that State-level entries require closure testing before use. Two of the three closure tests conducted here failed or revealed contradictions, and both failures are detectable only by executing the arithmetic against the State's own reported generation.

For the EPR instrument itself, the implication is that a leakage-avoidance obligation cannot be constructed on the present measurement base. Any future provision tying producer obligation to environmental outcome would require a leakage measurement that does not currently exist at any level of the system.

5.5 Limitations

The analysis covers 5.76 per cent of reported national generation once contradictory entries are excluded, and conclusions about the national mismanaged fraction cannot be drawn from it. The aquatic conversion rate is available from published literature but is calibrated on coastal populations, and all three usable jurisdictions are landlocked, so the index is reported as an interval with a separately labelled sensitivity rather than as a value. Generation itself is an estimate in every jurisdiction, so the quantity $G - C$ inherits the error in both terms. The reporting year is 2021-22 and the EPR obligation data derives from a subsequent portal record, so the two are not contemporaneous. Finally, the informal collection sector, which other sources in the corpus indicate may account for a substantial share of recovery in comparable economies, is not separately reported in the Indian instrument, and material recovered informally may appear as uncollected in these figures.

6. Conclusion

This study tested whether India's plastic-waste reporting architecture can evidence the environmental outcome that Extended Producer Responsibility exists to secure.

Of 34 jurisdictions reporting plastic waste generation, eight report collection in a form permitting a mismanaged-plastic calculation. One of those eight is internally contradictory, reporting a recycling quantity 4.5 times its reported collection. Four report collection exactly equal to generation, yielding a mismanaged fraction of zero by construction. Three jurisdictions yield a usable estimate, covering 5.76 per cent of reported national generation, with an uncollected fraction of 12.19 per cent.

Mass-balance closure testing found one State closing exactly, one closing to within 2.34 per cent, and one in which reported landfill alone exceeds the State's own reported generation by a factor of 1.19.

The EPR Leakage Avoidance Index is specified and evaluated in bounded form, giving 0.8781 as an upper bound for the usable subtotal. A published conversion rate from mismanaged waste to aquatic debris exists, bounded between 0.15 and 0.40 with a central value of 0.25, and applying it would narrow the index to between 0.9513 and 0.9817. That parameter is calibrated on populations within 50 km of a coast, and all three Indian jurisdictions whose reporting permits the calculation are landlocked. The jurisdictions for which the numerator is available are therefore precisely those outside the parameter's domain.

The conclusion is structural. The EPR instrument specifies obligation precisely, to the tonne and to the rupee, and specifies environmental outcome not at all. Until collection is reported as a measured quantity with its basis declared, and until a leakage term enters the reporting architecture, no quantity of producer compliance can be shown to have prevented any quantity of aquatic pollution.

Declaration on the Use of Generative Artificial Intelligence

During the preparation of this manuscript the author used a generative artificial intelligence tool (Anthropic Claude) to assist with structuring the analysis, drafting prose, and formatting the manuscript to the journal template. All source data were obtained from the published government and institutional documents cited in the References. The author reviewed, verified and edited all AI-assisted output against those primary sources, and takes full responsibility for the content, the accuracy of all figures and calculations, and the conclusions of this work. No data were generated, simulated or estimated by the AI tool. The AI tool is not listed as an author, in accordance with COPE authorship criteria.

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