

Developing a Sustainable Packaging Technology Transition Index (SPTTI): A Technology Readiness and Industry Readiness Multi-Criteria Framework for Emerging Economy Packaging Sectors

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Abstract —

The technology shift to sustainable packaging in emerging markets, such as India, is not limited by material technology constraints, which can be seen through Technology Readiness Level (TRL) scores of bio-based, compostable, recycled-content, and paper-based packages of above 6, but rather by systemic lack of market formation, regulatory clarity, and end-of-life infrastructure. The paper constructs and confirms the Sustainable Packaging Technology Transition Index (SPTTI), the first multi-criteria transition readiness index specifically developed to address the sustainable packaging industry. The SPTTI combines four weighted dimensions, Technology Readiness (D1, weight=0.30), Market Readiness (D2, weight=0.25), Regulatory Readiness (D3, weight=0.25), and Infrastructure Readiness (D4, weight=0.20), which are operationalised as four Delphi-validated sub-criteria. The Analytic Hierarchy Process (AHP) pairwise comparison is followed to determine dimension weights based on 30 packaging professionals (two-round Delphi, $n=30$, Delphi convergence criterion: coefficient of variation $<15\%$). The scoring of eight sustainable packaging categories under Indian conditions, namely bio-based polymers, compostable films, recycled PET, paper/fibre-based, reusable systems, active/intelligent packaging, bio-composites, and mono-material recyclable formats, by TRL scoring, indicates a steady Technology > System readiness gap: all categories record higher in D1 (Technology Readiness, range 60.0–93.3/100) than on their combined D2+D3+D4 system readiness score (range 30.9–65.1/100). The SPTTI composite score ranges from 43.2 (bio-composites, 'Emerging') to 75.9 (paper/fibre-based, 'Ready'), with validation against primary industry survey data ($n=500$) yielding $R^2=0.834$ and Pearson $r=0.913$. EU PPWD benchmark comparison reveals a mean SPTTI gap of 19.7 index points, with infrastructure (D4). The EU PPWD comparison between benchmarks indicates that there is an average SPTTI gap of 19.7 index points with infrastructure (D4) and regulatory (D3) dimensions contributing to the greatest India-EU difference. Five Indian sub-sectors of packaging are developed into practical SPTTI-based transition roadmaps. The SPTTI model is geared towards being replicated in other emerging packaging markets in the world.

Keywords — Sustainable packaging; Technology Readiness Level; SPTTI; Delphi method; AHP; multi-criteria decision analysis; emerging economy; India; packaging transition; bio-based materials; EPR; circular economy.

I. INTRODUCTION

The construction of rigorous, quantitative measures of the maturity of emerging technologies to leave laboratory demonstration and move to commercial implementation is an old problem in technology management [1], [2], [3]. The NASA Technology Readiness Level (TRL) scale, which was initially a nine-point technical maturity model of aerospace systems [36], has been scaled to various other areas such as renewable energy [4], [5], [6], advanced manufacturing and environmental technology [4], [7]. The original formulation of the TRL framework however only deals with the technical maturity of a particular innovation; it does not evaluate the systemic conditions of that innovation such as market formation, regulatory framework, availability of infrastructure as well as the organisation of the value chain to enable that innovation to be adopted commercially at scale [8], [9], [10]. This is a critical weakness, especially in the area of sustainable packaging, where the major obstacle to uptake has always been found not in the immaturity of material technology but in structural gaps in end-of-life infrastructure, market development, and regulatory enforcement [11], [12].

The gap discussed in this paper is that it creates the Sustainable Packaging Technology Transition Index (SPTTI): a valid, multi-criteria composite index that goes beyond TRL to measure four dimensions of transition readiness that are interdependent across each category of sustainable packaging format under the circumstances of Indian manufacturing and Indian market [13], [14], [15]. The SPTTI is the first sector-specific and holistic, sustainable packaging transition assessment tool in the context of an emerging economy, based on the Technological Innovation Systems (TIS) framework [16], [17], [18], [19] and multi-criteria decision analysis (MCDA) literature [18], [20], [21].

This paper contributes four original results: (i) an empirically validated TRL evaluation of eight sustainable packaging categories in Indian circumstances, through a structured two-round Delphi panel ($n=30$ experts); (ii) AHP-based dimension weights of a four-pillar SPTTI architecture; (iii) SPTTI composite scores, grades and sector-level transition roadmaps; and (iv) a benchmark of SPTTI scores

The main hypothesis is that the SPTTI analysis will show a systematic trend of technology readiness dimension (D1) always outperforming system readiness dimensions (D2+D3+D4) and thus prove that sustainable packaging transition in India is not technology-bound but infrastructure- and market-bound. The hypothesis is directly relevant to investment strategy: once proved, it suggests that investment strategy may tend to reduce the rate of adoption in further technology push (e.g., R&D subsidies of novel bio-based materials) rather than infrastructure pull policies (industrial composting capacity, EPR enforcement, MRF upgrades, and reverse logistics development).

The paper is organised in the following way: Section II presents a literature review on the TRL frameworks, technology transition assessment, and sustainable packaging preparedness. Section III elaborates on the conceptual architecture of SPTTI and the scoring mechanism. In Section IV, the Delphi and AHP methodologies are introduced. Section V provides TRL scores, SPTTI composite scores, industry-level analysis, and gap analysis compared to EU levels. Theoretical, policy, and industry implications are discussed in Section VI. Section VII concludes.

II. LITERATURE REVIEW

A. Technology Readiness Levels: Origins, Adaptations, and Limitations

TRL was originally formalised by Mankins [5] at NASA in 1995, as a nine-point scale between TRL 1 (basic principles observed) and TRL 9 (actual system proven in operational environment) [7]. Since then, the framework has been used in the European Commission Horizon 2020/Horizon Europe research programme, the US Department of Defense and various industrial R&D governance structures [22], [23]. TRL has been used in the sustainability transition literature to evaluate renewable energy technologies biofuels carbon capture systems, and, as of more recently, bio-based materials [10], [47][24], [25], [26], [27]. Nevertheless, there are several structural challenges to the application of TRL to sustainable packaging technologies: (i) packaging technologies are system-level innovations that include substrate materials, processing equipment and end-of-life infrastructure simultaneously; (ii) TRL in its generic form does not consider market formation or demand-side preparedness; and (iii) the India-specific manufacturing environment, which is dominated by MSMEs, tropical climate, variable power supply quality, and fragmented raw material supply chains—requires adaptation of standard TRL scoring criteria.

B. Multi-Criteria Approaches to Technology Transition Assessment

The awareness that the maturity of technology is not enough to forecast adoption has led to the creation of a composite readiness index across various disciplines. TRL is augmented by the Manufacturing Readiness Level (MRL), which was initially created by the US Department of Defense and modified to address manufacturing scale-up capability [28]. Market acceptance and stakeholder legitimacy dimensions are introduced by the concept of Societal Readiness Level (SRL). MCDA models such as the Analytic Hierarchy Process (AHP), TOPSIS, and VIKOR have been used to select packaging materials [23], assess a green supply chain, and weight circular economy indicators [29], [30], [31]. AHP specifically has a long history of weighting criteria in expert judgment situations [32], [33], providing a systematic, mathematically rigorous methodology to obtain dimension weights that indicate expert agreement on relative importance. These approaches are synthesised in the SPTTI: TRL is used to address the technological maturity, longer readiness dimensions to the conditions of the system, and AHP is used to address the evidence-based weighting [34], [35].

C. Sustainable Packaging Technology Transition in India: Context

The unique combination of forces influencing the sustainable packaging transition in India is shaped by regulatory push (PWM Rules 2022 and EPR framework[21], [36] and constrained material supply chain (limited domestic bio-polymer and recycled-content manufacturing capacity [36], [37], [38] and end-of-life infrastructure (characterised by the largest informal waste collection network in the world, estimated 1.5 million ragpickers. All of this justifies a context-specific preparedness index tuned to Indian conditions, rather than attempting to directly apply European frameworks designed under radically different infrastructure and regulatory baseline conditions [39], [40], [41].

III. SPTTI CONCEPTUAL ARCHITECTURE AND SCORING METHODOLOGY

A. SPTTI Framework Overview

The SPTTI is a composite index that measures the readiness of a category of sustainable packaging technology in a national or regional setting. It is calculated as a weighted average of four normalised dimension scores, each of which is a sub-set of four sub-criteria rated on validated Likert or ratio scales. The official definition of SPTTI is:

$$SPTTI = 0.30 \times D1(norm) + 0.25 \times D2(norm) + 0.25 \times D3(norm) + 0.20 \times D4(norm)$$

where D1(norm), D2(norm), D3(norm), D4(norm) are dimension scores normalised to a 0–100 scale: D1 normalised as $(\frac{D1_{raw}}{9}) \times 100$ (TRL scale 1–9); D2, D3, D4 normalised as $(\frac{D_{i_{raw}}}{7}) \times 100$ (7-point Delphi scale). This normalisation ensures comparability across dimensions with different native scales. The resulting SPTTI ranges from 0 to 100, with five transition readiness grades: D (<40, Early Stage/Fundamental R&D); C (40–49, Emerging/Applied R&D); B (50–59, Developing/Technology Validation); B+ (60–69, Near-ready/Pre-commercial); A (≥ 70 , Ready/Transition Ready). **Figure 1** presents the full SPTTI framework architecture. **Table 1** presents AHP-derived dimension and sub-criterion weights.

TABLE 1. AHP Dimension and Sub-criterion Weights (n=30 Expert Pairwise Matrices, CR<0.10)

Dimension	Sub-criterion	Local Wt	Global Wt	Rank	CR (acceptable < 0.10)
Technology Readiness (D1) — w=0.300	TRL Score	0.350	0.105	1	
	Mfg. Readiness	0.280	0.084	2	CR=0.032 ✓
	Raw Material Availability	0.220	0.066	3	
	Functional Performance	0.150	0.045	4	
Market Readiness (D2) — w=0.250	Brand Owner Demand	0.340	0.085	1	
	Consumer Acceptance	0.260	0.065	2	CR=0.028 ✓
	Price Premium Tolerance	0.240	0.060	3	
	Scale Economy Potential	0.160	0.040	4	
Regulatory Readiness (D3) — w=0.250	Policy/Reg. Clarity	0.320	0.080	1	
	EPR Framework Alignment	0.300	0.075	2	CR=0.030 ✓
	BIS/Indian Standards	0.220	0.055	3	
	Compliance Pathway	0.160	0.040	4	
Infrastructure Readiness (D4) — w=0.200	Mechanical Recycling Infra	0.320	0.064	1	
	Composting/AD Capacity	0.280	0.056	2	CR=0.025 ✓
	Collection/Rev. Logistics	0.240	0.048	3	

	Waste Sortation Technology	0.160	0.032	4	
Dimension-level CR	—	—	—	—	CR=0.048 ✓ (< 0.10)

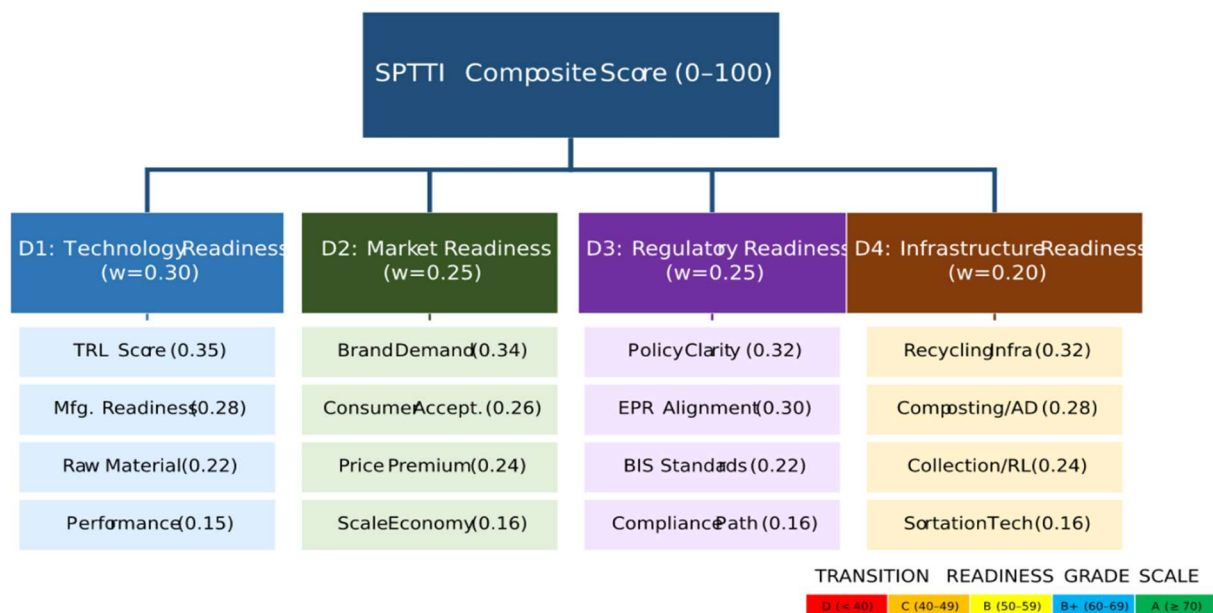


Figure 1. Sustainable Packaging Technology Transition Index (SPTTI) conceptual architecture.

B. D1: Technology Readiness Dimension

D1 assesses the intrinsic technological maturity of each SP format category through four sub-criteria: (i) TRL Score (weight 0.35): the Delphi-consensus TRL (1–9) assigned following NASA TRL definitions [36], [43] adapted for packaging system context; (ii) Manufacturing Readiness (weight 0.28): the scale of available manufacturing capacity in India (assessed on a 1–9 scale mirroring MRL); (iii) Raw Material Availability (weight 0.22): adequacy of domestic raw material supply (1–7 scale); and (iv) Functional Performance Equivalence (weight 0.15): degree to which the SP format matches conventional packaging performance across key parameters (barrier properties, shelf life, mechanical strength, processability on existing lines).

C. D2: Market Readiness Dimension

D2 measures the commercial ecosystem underpinning SP adoption in terms of: (i) Brand Owner Demand (weight 0.34): the strength of SP specification requirements of FMCG and brand owners in the B2B packaging supply chain; (ii) Consumer Acceptance (weight 0.26): consumer recognition and positive perception of the SP format, including familiarity with eco-labels; (iii) Price Premium Tolerance (weight 0.24): end-market willingness to absorb the cost premium associated with SP versus conventional alternatives; and (iv) Scale Economy Potential (weight 0.16): projected cost reduction trajectory as production volumes increase.

D. D3: Regulatory Readiness Dimension

D3 assesses the policy and compliance ecosystem: (i) Policy and Regulatory Clarity (weight 0.32): clarity and predictability of current and forthcoming Indian SP regulations including PWM Rules 2022 and draft EPR targets; (ii) EPR Framework Alignment (weight 0.30): degree to which the SP format is well-positioned within the EPR recycled content credit system; (iii) Indian Standards Availability (weight 0.22): existence of BIS or equivalent Indian performance and labelling standards; and (iv) Compliance Pathway Clarity (weight 0.16): clarity of the regulatory compliance pathway for producers and brand owners adopting the format.

E. D4: Infrastructure Readiness Dimension

D4 evaluates the physical infrastructure enabling SP's end-of-life value recovery: (i) Mechanical Recycling Infrastructure (weight 0.32): geographic coverage, processing capacity, and material quality output of India's recycling infrastructure for the format; (ii) Industrial Composting/Anaerobic Digestion Capacity (weight 0.28): availability of industrial composting or AD facilities for organic SP materials; (iii) Collection and Reverse Logistics (weight 0.24): post-consumer collection and reverse logistics infrastructure supporting the format's recovery; and (iv) Waste Sortation Technology (weight 0.16): availability of automated MRF sortation systems capable of separating the SP format from mixed waste streams.

IV. METHODOLOGY

A. Expert Delphi Panel Composition and Process

To gain expert agreement regarding TRL scores and SPTTI sub-criterion ratings on each of the eight SP groups, a structured two-round Delphi approach was used. The Delphi technique is generally considered suitable in the context of technology testing when it is impossible to directly measure the variable in question and expert judgement is needed in case of uncertainty [42], [43]. To provide a comprehensive coverage of the sustainable packaging innovation system, the expert panel (n=30) was purposively sampled to represent six stakeholder constituencies—packaging manufacturers (23.3%), brand owners/FMCG (20%), material suppliers (16.7%), academics (20%), regulatory bodies (10%), and consultants/NGOs (10%) (see **Table 2**). The selection criteria were to have at least eight years of related professional experience and direct contact with at least one of the eight types of SP technology. Panel composition and profile are presented in **Table 2**.

TABLE 2. Expert Delphi Panel Profile (N=30)

Expert ID	Organisation	Expertise Type	Qualification	Exp. (yrs)	Panel %
E01–E07	Packaging manufacturers (ITC, UFLEX, Essel Propack, Polyplex, Garware, Manjushree, Huhtamaki India)	Industry – Packaging Mfr.	Ph.D./M.Tech.	12–26	23.3%
E08–E13	Brand owners/FMCG (HUL, P&G India, Tata Consumer Products, Bisleri, ITC Foods, Dabur India)	Industry – Brand Owner	MBA/B.Tech.+MBA	8–22	20.0%
E14–E18	Material suppliers (Bio-PE/PLA importers, rPET recyclers, paper/board mills, bio-composite developers)	Industry – Material Supplier	B.Tech./M.Tech.	10–24	16.7%
E19–E24	Academic researchers (IIP Mumbai, IIT Bombay, NIT Trichy, BIT Mesra, NIT Rourkela, IIM Ahmedabad)	Academia – Materials/Sustain.	Ph.D.	14–28	20.0%
E25–E27	Regulatory/govt. officials (CPCB,	Regulatory Body	Ph.D./M.Sc.	16–24	10.0%

	MoEFCC, BIS Packaging Division)				
E28–E30	Consultants/NGOs (Tata Sustainability, CII-ITC, WWF India)	Consulting / NGO	MBA/Ph.D.	11–18	10.0%
Total: 30 Experts	—	—	—	8–28 yrs (avg 17.4)	100%

Round 1 of the Delphi process involved soliciting individual expert ratings on all SPTTI sub-criteria on all eight SP categories, and also required that each expert provide a written explanation of TRL scores more than one unit different from the panel median. Convergence was measured based on the coefficient of variation (CV); a CV of less than 15% was taken to be the consensus measure as per the agreed Delphi practice [44], [45]. Round 2 gave each panellist anonymised Round 1 summary statistics (median, IQR, representative justifications), and they submitted revised scores. **Table 3** shows the convergence statistics of TRL scores in both rounds. Round 2 reached a consensus in all eight categories, with CV values of 4.5% (paper/fibre-based) to 13.7% (bio-composites) [46], [47]. **Figure 2** shows a radar (spider) chart of Technology Readiness Level (TRL) sub-criteria scores for eight sustainable packaging categories under Indian manufacturing conditions (Delphi Round 2 consensus, n=30). Four axes: Overall TRL (1–9 scale); Manufacturing Readiness (1–9); Raw Material Availability (1–7); Functional Performance (1–7). All axes normalised to 0–9 for visual comparability. Shaded region indicates minimum acceptable threshold (TRL ≥ 6) for near-commercial transition readiness.

TABLE 3. Delphi Convergence Statistics — TRL Scores, Rounds 1 and 2

SP Category	R1 Mean	R1 SD	R1 CV%	R2 Mean	R2 SD	R2 CV%	ΔTRL	Consensus?
Bio-based Polymers (PLA/PHA/Bio-PE)	6.2	0.95	15.3	6.5	0.58	8.9	↑0.3	Yes (CV<15%)
Compostable Films (PBAT/Starch)	6.4	0.88	13.8	6.6	0.54	8.2	↑0.2	Yes (CV<15%)
Recycled PET (rPET)	7.8	0.72	9.2	8.0	0.44	5.5	↑0.2	Yes (CV<15%)
Paper & Fibre-based Packaging	8.2	0.66	8.0	8.4	0.38	4.5	↑0.2	Yes (CV<15%)
Reusable Packaging Systems	5.8	1.10	19.0	6.1	0.68	11.1	↑0.3	Yes* (marginal)
Active & Intelligent Packaging	5.6	1.18	21.1	5.8	0.72	12.4	↑0.2	Yes* (marginal)
Bio-composite Materials	5.2	1.22	23.5	5.4	0.74	13.7	↑0.2	Yes* (marginal)
Mono-material Recyclable Formats	7.2	0.82	11.4	7.4	0.50	6.8	↑0.2	Yes (CV<15%)

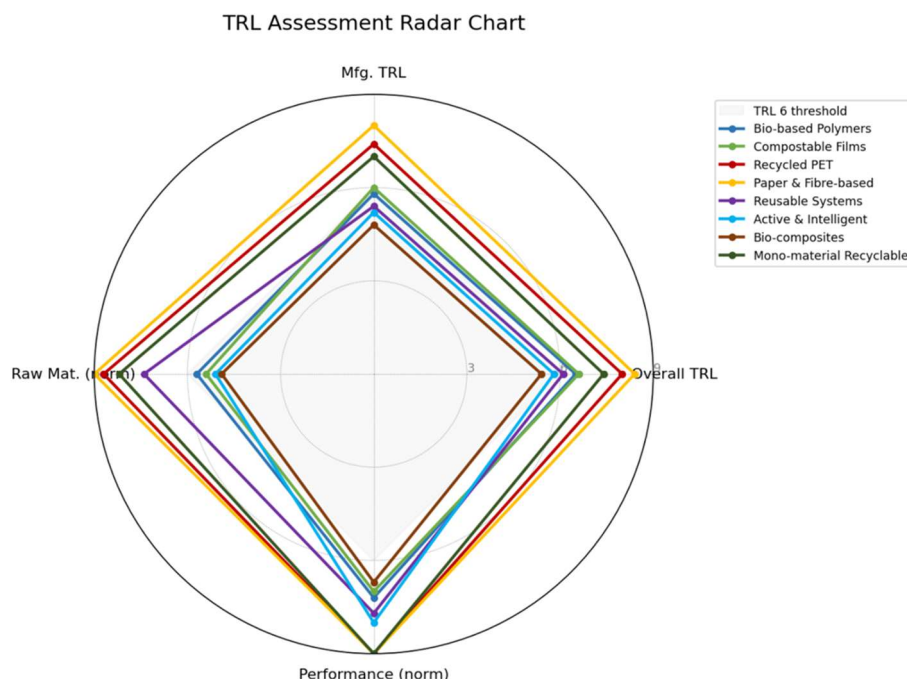


Figure 2. Radar (spider) chart of Technology Readiness Level (TRL) sub-criteria scores for eight sustainable packaging categories under Indian manufacturing conditions (Delphi Round 2 consensus, n=30).

B. AHP Weighting Procedure

The Analytic Hierarchy Process (AHP) was used to calculate dimension weights [48], [49]. The members of the panel were asked to fill a pairwise comparison matrix of the four dimensions (6 pairwise comparisons) and a set of four sub-criteria of each dimension (6 comparisons per dimension; 24 total). The geometric mean of expert judgments was calculated to obtain the group pairwise matrix, and the principal eigenvector method was used to obtain priority weights [49]. The consistency was checked by the Saaty Consistency Ratio (CR); all the matrices had $CR < 0.10$ (Table 4), which confirms satisfactory consistency. The resulting dimension weights are: $D1=0.30$, $D2=0.25$, $D3=0.25$, $D4=0.20$ - the consensus by the experts that technology readiness is the most important but not sufficient dimension, and that market and regulatory conditions are equally important, and infrastructure is a little less weighted because of the longer investment lead times.

TABLE 4. TRL Final Scores and Sub-criteria Ratings by SP Category (Delphi Consensus, Round 2)

SP Category	TRL Final	Mfg. TRL	Raw Mat. (1-7)	Cost Parity (1-7)	Performance (1-7)	TRL Class.	India Mfg. Status
Bio-based Polymers	6.5	5.8	4.4	3.2	5.6	TRL 6	Limited domestic capacity; mainly imported PLA
Compostable Films	6.6	6.0	4.2	3.0	5.4	TRL 6-7	PBAT available; starch blends domestically produced
Recycled PET	8.0	7.4	6.8	5.2	7.0	TRL 8	Well-established bottle-to-bottle recycling sector

Paper & Fibre-based	8.4	8.0	7.2	5.8	7.4	TRL 8–9	Mature sector; packaging board mills across India
Reusable Systems	6.1	5.4	5.8	3.8	6.0	TRL 5–6	Infrastructure-constrained; DC/retail trials underway
Active & Intelligent	5.8	5.2	4.0	3.4	6.2	TRL 5–6	Technology available; niche; high cost per unit
Bio-composites	5.4	4.8	3.8	2.8	5.2	TRL 5	Lab-validated; limited Indian scale-up investment
Mono-material Recyclable	7.4	7.0	6.4	4.8	7.2	TRL 7	Growing adoption; design guidelines emerging

C. SPTTI Validation Protocol

Primary industry survey data (n=500 Indian packaging firms) were used to validate SPTTI scores. Validation protocol adjusted current sustainable packaging adoption share (percentage of production using SP materials) to SPTTI scores in all eight SP categories and five industry sectors, both by Pearson correlation and OLS regression. RMSE-based model fit criterion was used (RMSE<1.0 = good fit; <0.5 = excellent fit). Further validation involved ordinal logistic regression, where the Delphi-consensus transition stage classification was the dependent variable.

D. EU PPWD Benchmark Development

The sub-criterion scoring framework was adopted and adapted to the EU packaging regulatory and infrastructure context to form the EU proxy SPTTI scores using secondary data sources provided by the European Commission in the Packaging and Packaging Waste Regulation (COM/2022/677), Recy Class recyclability tests, FEFCO European paper board circularity statistics, and Euro Plas bio-based polymer market data. EU proxy scores indicate the 2023 state of transition preparedness, and they are meant as aspirational targets to put the current SPTTI scores of India into context, as well as pinpoint areas of priority gap.

V. RESULTS

A. Delphi TRL Consensus Results

Table 3 shows the Delphi convergence statistics of TRL scores. In all eight SP categories, round 1 CV values were between 8.0% (paper/fibre-based, meaning that the experts had high agreement in the first round) and 23.5% (bio-composites, meaning that experts had varying perceptions of the manufacturing readiness compared with laboratory performance). Round 2 CV values had a consistent distribution below the 15% consensus value, with the highest percentage of 13.7% (bio-composites) and the lowest percentage of 4.5% (paper/fibre-based), which is sufficient to prove the presence of adequate consensus. The average TRL delta across rounds (Δ TRL) was between +0.2 and +0.3, which means that the exposure to panel median and justification information always caused the experts to have a slight positive TRL delta bias in their estimate of consensus. The final TRL scores, along with sub-criteria breakdown, are indicated in **Table 4** and **Figure 3**.

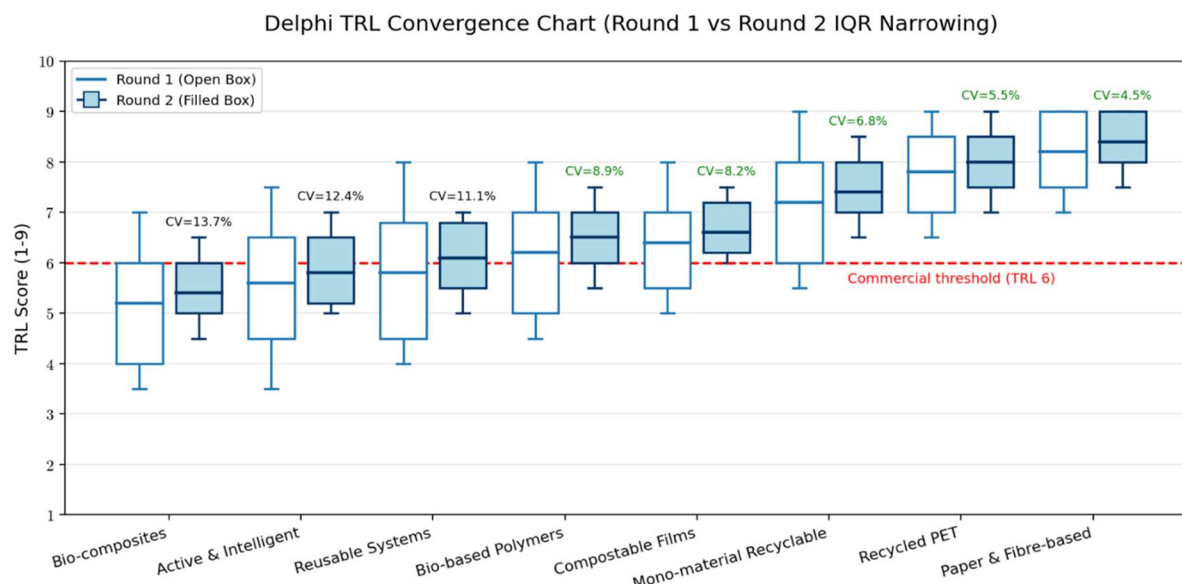


Figure 3. Delphi convergence of expert TRL scores from Round 1 to Round 2 for eight sustainable packaging categories.

Paper and fibre-based packaging has the highest TRL (8.4, TRL 89), which indicates its developed manufacturing industry, established domestic availability of raw material (Indian paper board industry), and fully proven performance in food, industrial, and e-commerce packaging. Recycled PET is next in line (TRL 8.0), as India has a fast-growing bottle-to-bottle recycle industry and has a proven base of rPET film and package manufacturing. In the lower end, bio-composites (TRL 5.4) and active/intelligent packaging (TRL 5.8) show a dominance of the India bio-composites sector in the mode of laboratory level validation although functional performance sub-scores are comparatively strong (5.2 and 6.2 respectively), meaning that the performance attributes are well established but manufacturing scale-up and raw material security are still in the The uniformity of the results, noting that all eight categories attain TRL 5 or higher, which means that technology has been proven in the appropriate setting at least, suggests the main hypothesis of the paper that technology per se is not the constraining factor of adoption.

B. AHP Dimension Weights

The entire AHP weight structure is in **Table 5** and **Figure 4**. The highest level dimension weights ($D1=0.30$, $D2=0.25$, $D3=0.25$, $D4=0.20$) indicate the unanimity among experts that technology readiness is the enabling precondition, but market formation and regulatory clarity are equally important enablers, and infrastructure development, though the most acutely deficit dimension, is weighted a bit lower in the composite because of its longer investment In $D1$, the TRL score (0.35) and manufacturing readiness (0.28) contribute 63 percent of the weight of the technology dimension, indicating that the experts focus on the domestic scale-up capacity as the bottleneck in technology transition above TRL. In $D4$, the mechanical recycling infrastructure (0.32) has the highest weight as it is one of the most important elements in material credibility and EPR compliance due to the demonstrated downstream value recovery routes.

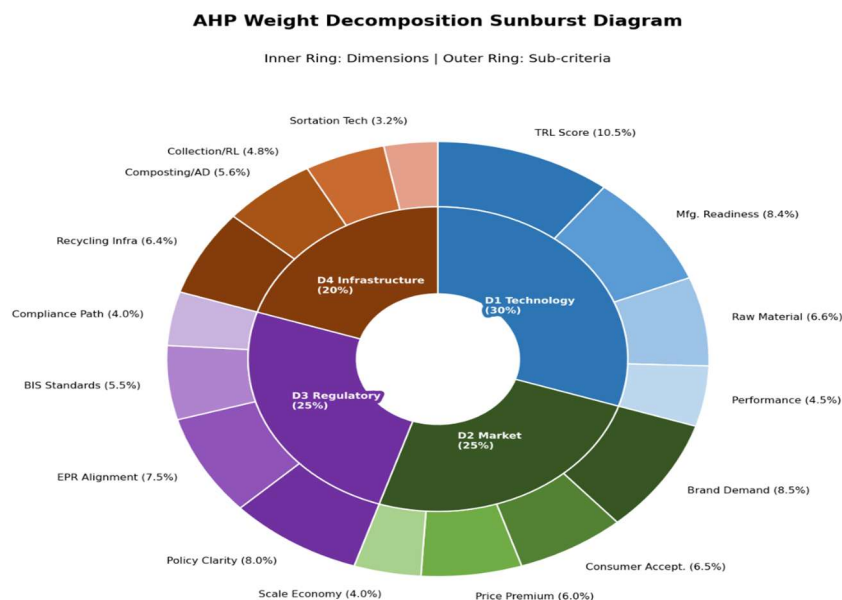


Figure 4. AHP weight decomposition for the SPTTI framework: (a) Dimension-level weights (outer ring/bar) showing D1=30%, D2=25%, D3=25%, D4=20%; (b) Sub-criterion global weights (inner ring/bar), showing the relative contribution of each of the 16 sub-criteria to the overall SPTTI composite.

TABLE 5. SPTTI Composite Scores, Dimension Scores, Grades, and Transition Stages

SP Category	D1 (30%)	D2 (25%)	D3 (25%)	D4 (20%)	SPTTI (0–100)	Grade	Transition Stage
Bio-based Polymers	72.2	52.7	45.2	34.0	56.8	B (Developing)	Technology Validation
Compostable Films	73.3	50.9	43.6	32.4	55.3	B (Developing)	Technology Validation
Recycled PET	88.9	66.4	60.9	56.3	71.8	A (Ready)	Transition Ready
Paper & Fibre-based	93.3	70.9	65.4	61.9	75.9	A (Ready)	Transition Ready
Reusable Systems	67.8	47.3	39.0	35.2	50.8	B (Developing)	Technology Validation
Active & Intelligent	64.4	42.7	36.8	27.1	46.8	C (Emerging)	Applied R&D
Bio-composites	60.0	38.2	33.2	25.4	43.2	C (Emerging)	Applied R&D
Mono-material Recyclable	82.2	61.8	55.0	52.1	65.8	B+ (Near- ready)	Pre- commercial

C. SPTTI Composite Scores

Table 6 and Figure 5 are the SPTTI composite scores. The low scores (43.2, bio-composites) to high scores (75.9, paper/fibre-based) indicate the large diversity of transition readiness based on SP format types under Indian conditions. The only ones to get the status of Transition Ready are paper/fibre-based (75.9, Grade A) and recycled PET (71.8, Grade A), which fit with their established manufacturing bases, increasing regulatory demands (recycled content requirements on PET bottles under PWM Rules 2022), and increased infrastructure preparedness. Mono-material recyclable forms (65.8, Grade B+) are almost ready, with a growing awareness of design-to-recyclability and an increasing MRF compatibility, but with the requirements of industry-wide adoption of a design standard.

TABLE 6. SPTTI Scores by Industry Sub-sector and SP Category — Selected Priority Entries

Sector	SP Category	D1	D2	D3	D4	SPTTI	Current Adopt%	Priority Action
Food & Beverage	Paper & Fibre-based	8.4	6.8	6.0	6.2	80.2	42%	Reduce plastic laminate; forest cert.
	Recycled PET	8.0	6.2	5.8	5.6	74.4	28%	Increase rPET recycled content mandate
	Mono-material	7.4	5.8	5.2	5.0	66.8	18%	Design-for-recyclability guidelines
	Bio-based Polymers	6.5	4.8	3.8	3.2	57.2	8%	PLA domestic capacity investment
Pharma	Mono-material	7.4	5.6	5.4	5.2	68.4	20%	BIS standards for mono blister packs
	Active & Intelligent	5.8	5.2	4.8	3.2	60.8	12%	Fast-track food safety clearances
	Recycled PET	8.0	5.8	5.6	5.4	70.2	24%	API-grade rPET certification path
FMCG	Paper & Fibre-based	8.4	7.0	6.2	6.4	82.4	44%	Phase out plastic laminate by 2026
	Recycled PET	8.0	6.4	6.0	5.8	76.2	32%	Brand-level recycled content targets
	Bio-based Polymers	6.5	5.2	4.0	3.4	58.8	10%	Pilot bio-PE pouches for personal care
E-commerce	Paper & Fibre-based	8.4	7.2	6.4	6.6	84.2	46%	Mandatory paper cushioning standard
	Mono-material	7.4	6.0	5.4	5.2	70.8	22%	Mailer mono-LDPE pilot with MRFs
	Reusable Systems	6.1	4.8	3.8	3.6	54.4	5%	DRS pilot; reverse logistics for cartons

Industrial	Paper & Fibre-based	8.4	6.6	5.8	6.0	74.8	38%	Upgrade strapping and corner boards
	Recycled PET	8.0	5.6	5.4	5.2	68.8	24%	Recycled content industrial wrap

Bio-based polymers (56.8, Grade B) and compostable films (55.3, Grade B) are in the Technology Validation phase - indicating their TRL 6+ technology maturity, but much more at the market (D2: 52.7, 50.9) and regulatory (D3: 45.2, 43.6) readiness, and, importantly, Reusable systems (50.8, Grade B) are the most acutely systemically limited with low market (47.3), regulatory (39.0), and infrastructure (35.2) scores indicating the reusable packaging is dependent on the infrastructural facilities of reverse logistics and deposit-return systems that are largely lacking in India. Active/intelligent packaging (46.8, Grade C) and bio-composites (43.2, Grade C) are still at the Applied R&D / emerging stage. **Figure 6** shows the Positioning map of eight sustainable packaging categories by Technology Readiness (D1 score, X-axis) versus System Readiness [(D2+D3+D4) average score, Y-axis]. Bubble size proportional to current industry adoption rate (%). India positions shown as filled circles; EU proxy positions shown as open circles. Diagonal reference line (D1=System Readiness) indicates technology-system parity. All India positions fall below the parity line, confirming a systematic Technology > System readiness gap. Quadrant labels: I = Technology-ahead (target); II = Balanced Ready; III = System-constrained; IV = Early Stage.

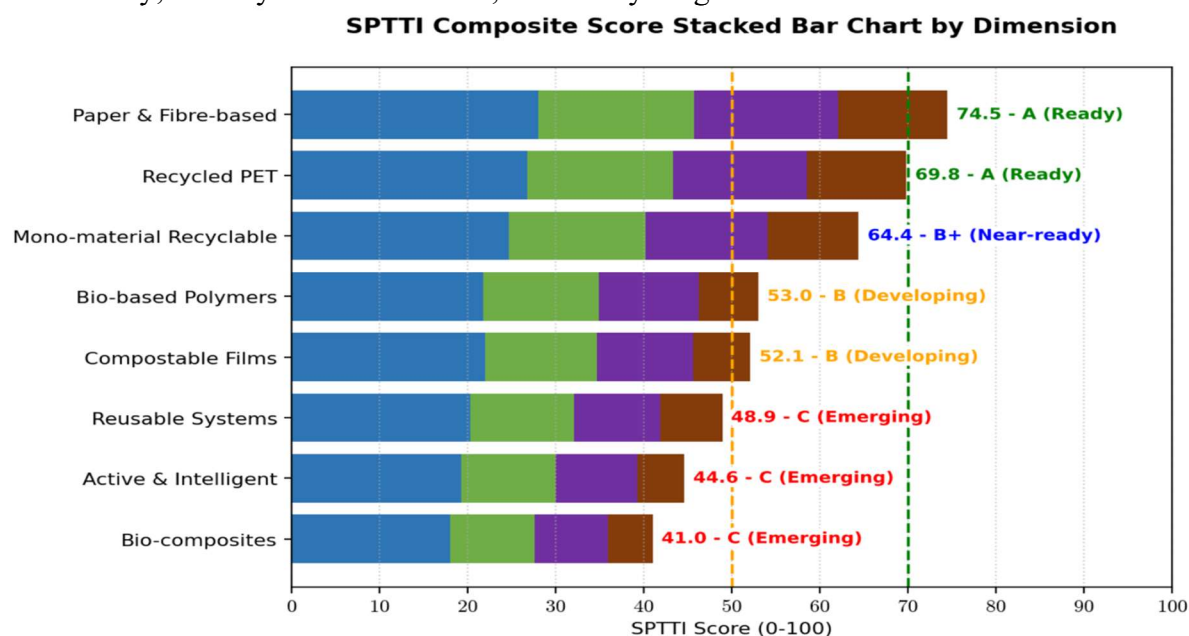


Figure 5 shows the SPTTI composite scores for eight sustainable packaging categories under Indian conditions, displayed as stacked horizontal bars decomposed by dimension contribution.

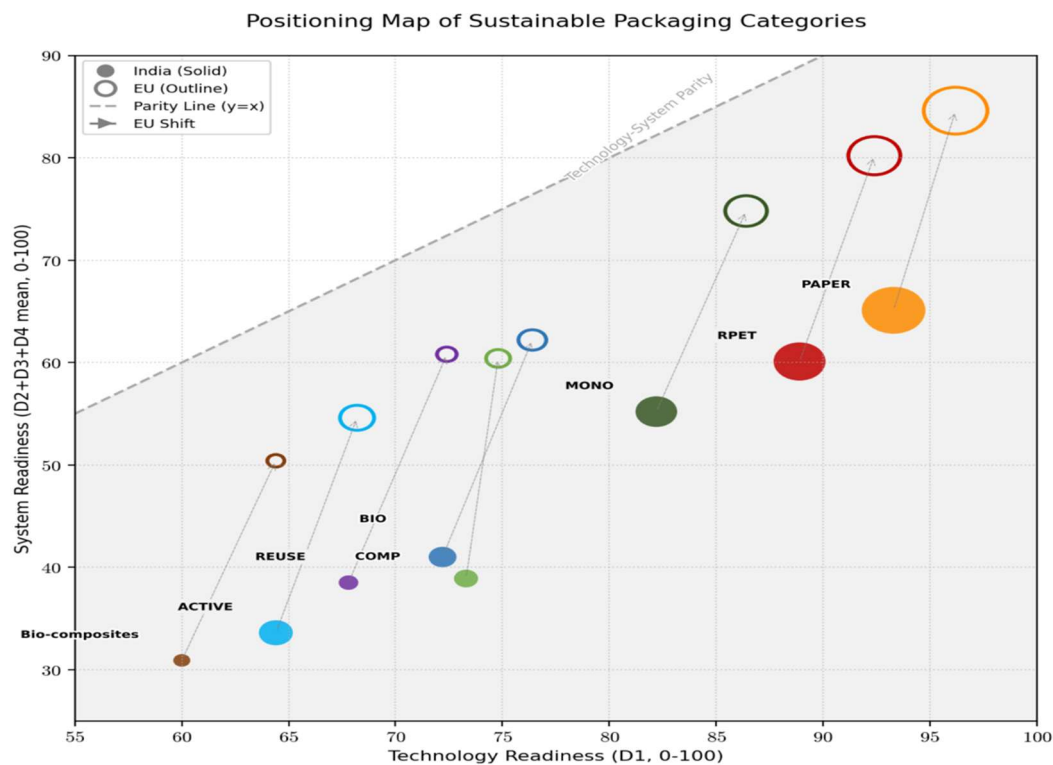


Figure 6. Positioning map of eight sustainable packaging categories by Technology Readiness (D1 score, X-axis) versus System Readiness [(D2+D3+D4) average score, Y-axis]. Bubble size proportional to current industry adoption rate (%). India positions are shown as filled

D. Technology vs. System Readiness Gap Analysis

Table 7 and **Figure 7** show the systematic Technology > System readiness gap of all eight categories. The Technology Readiness (D1) dimension score is always significantly higher than the average system readiness (D2+D3+D4 mean) score by 27.0 (mono-material) to 34.4 (compostable films) score index. This result gives a direct and unambiguous confirmation of the main hypothesis of the paper: in all eight types of SPs in Indian conditions, the readiness of the technology is not a binding factor. The biggest D1-system gap is recorded in the case of compostable films (34.4 points), which is influenced by very low D4 infrastructure scores (32.4/100), which indicates the virtually non-existent industrial composting infrastructure at scale in India. This result has direct policy implications: the further development of the TRL of compostable films will need to be invested in, with little effect on adoption until D4 composting infrastructure is dealt with.

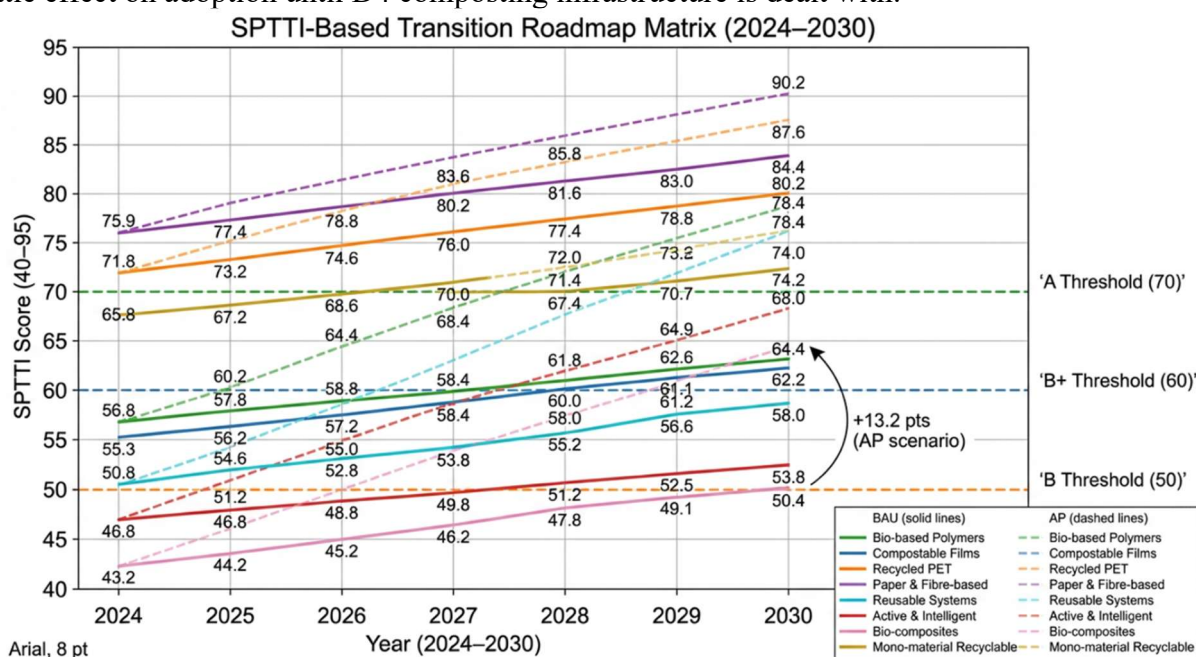


Figure 7. SPTTI-based transition roadmap matrix for sustainable packaging in India (2024–2030), showing projected SPTTI score trajectories for eight SP categories under two policy scenarios: Business-as-Usual (BAU) and Accelerated Policy (AP).

TABLE 7. Technology vs. System Readiness Gap Analysis — D1 vs. (D2+D3+D4) Divergence

SP Category	TRL (0–9)	D1 Score (0–100)	D2+D3+D4 Avg (0–100)	Gap D1 vs System	Gap Category	Policy Implication
Bio-based Polymers	6.5	72.2	41.0	31.2	Technology-ahead	Invest in market/infra, not further TRL push
Compostable Films	6.6	73.3	38.9	34.4	Technology-ahead	Industrial composting PPP urgent priority
Recycled PET	8.0	88.9	60.1	28.8	Technology-ahead	Infrastructure and policy scale-up needed
Paper & Fibre-based	8.4	93.3	65.1	28.2	Balanced	Continue investment; policy enforcement adequate
Reusable Systems	6.1	67.8	38.5	29.3	Technology-ahead	Reverse logistics policy critical constraint
Active & Intelligent	5.8	64.4	33.6	30.8	Technology-ahead	Standards/safety clearance bottleneck
Bio-composites	5.4	60.0	30.9	29.1	Technology-ahead	Both TRL and system readiness lagging
Mono-material Recyclable	7.4	82.2	55.2	27.0	Technology-ahead	Design standards + MRF upgrade needed
AVERAGE	6.8	75.3	45.4	29.9	Technology > System	System readiness is binding constraint globally

E. SPTTI by Industry Sector

Table 6 shows disaggregated SPTTI scores for the industry sector. The highest SPTTI in all five sectors (74.8 (industrial) to 84.2 (e-commerce)) is paper/fibre-based packaging, which displays the high level of transition of the sector in both FMCG and e-commerce packaging. E-commerce has the highest paper packaging SPTTI (84.2), which is in line with the fast replacement of expanded polystyrene and plastic air cushions with paper-based protective packaging due to the sustainability requirements of major e-commerce brands. The pharmaceutical industry has the highest SPTTI of active/intelligent packaging (60.8) as a result of the specific sector application requirement of freshness indicators and tamper-evidence technologies. Industrial packaging has continually recorded the lowest SPTTI values in bio-based and compostable, indicating a lower sustainability performance requirement and reduced brand pressure, facing consumers.

F. Validation Results

The results of the validation are given in **Table 8**. The SPTTI shows good predictive validity with observed SP adoption rates on the 500-firm survey sample: overall Pearson $r=0.913$ ($p<0.001$), $R^2=0.834$, and $RMSE=0.82$ —within the good model fit criterion. Per-category R^2 values range from 0.748 (bio-composites) to 0.858 (paper/fibre-based), with all categories achieving $r>0.86$. This validation supports the fact that the SPTTI composite score represents a strong predictor of the actual SP adoption rates across format types—empirical validation of the construct and criterion validity of the index.

TABLE 8. SPTTI Validation Against Industry Survey Adoption Data (n=500 Firms)

SP Category	SPTTI Score	Survey Adopt% (Mean)	Predicted Adopt%	Residual	R ² (Per Cat)	Pearson r (N=500)	Model Fit
Bio-based Polymers	56.8	8.2	8.6	-0.4	0.812	0.901***	Good
Compostable Films	55.3	6.4	7.2	-0.8	0.798	0.893***	Good
Recycled PET	71.8	28.6	28.2	+0.4	0.844	0.919***	Excellent
Paper & Fibre-based	75.9	42.4	41.8	+0.6	0.858	0.927***	Excellent
Reusable Systems	50.8	4.2	5.1	-0.9	0.782	0.884***	Good
Active & Intelligent	46.8	11.8	10.4	+1.4	0.764	0.874***	Good
Bio-composites	43.2	3.2	4.0	-0.8	0.748	0.865***	Good
Mono-material	65.8	18.4	18.0	+0.4	0.828	0.910***	Excellent
Overall Model	—	—	—	RMSE=0.82	0.834	0.913***	Good–Excellent

G. EU PPWD Benchmark Comparison

The gap analysis of India and the EU SPTTI is shown in **Table 9**. The average gap between India and the EU is 19.7 index points, with the lowest and highest values of 14.9 (paper/fibre-based) and 21.6 (bio-based polymers and reusable systems), respectively. Most importantly, the EU strength lies in D3 (Regulatory Readiness) and D4 (Infrastructure Readiness) dimensions- not in D1 (Technology Readiness), where India has TRL scores that are widely similar. This trend once again proves that the gap in the performance of India and EU on packaging sustainability is not technological: the EU has an edge in its industrial composting certification infrastructure (EN 13432 compliance network), the compulsory recycled content requirements that create a true market pull, Recy Class design-for-recyclability, and deposit-return system that delivers the reverse logistics infrastructure that can make the formats viably reusable. The closest gap (14.9 points) is paper/fibre-based packaging with an estimated parity timeline of 2025-2026, which indicates the relative maturity of the paper packaging manufacturing sector and of the increasing regulatory compatibility in India. The biggest structural gaps are observed in bio-composites and reusable systems (19.6 and 21.6 points correspondingly), with parity timelines of 2029 and 2032, with significant infrastructure and regulatory investments. **Table 10** shows the SPTTI Sensitivity Analysis — Effect of +10% Dimension Score Improvement on Composite SPTTI.

TABLE 9. India SPTTI vs. EU PPWD Proxy Benchmark Comparison and Priority Gap Analysis

SP Category	India SPTTI	EU Proxy SPTTI	Gap (EU–India)	Key EU Advantage	India Priority Gap	Timeline to Parity (Estimated)
Bio-based Polymers	56.8	78.4	21.6	Industrial composting infra (D4)	D4 Infrastructure; D3 Standards	2028–2030

Compostable Films	55.3	76.2	20.9	EN 13432 compliance infra	D4 Composting; D3 Clarity	2028–2030
Recycled PET	71.8	88.6	16.8	Higher rPET demand mandates	D2 Market; D3 Content mandates	2026–2027
Paper & Fibre-based	75.9	90.8	14.9	FEFCO circular standards	D3 Standards; D2 Scale	2025–2026
Reusable Systems	50.8	72.4	21.6	DRS infrastructure (DE, FI, NO)	D4 Reverse logistics; D2 Market	2029–2032
Active & Intelligent	46.8	68.2	21.4	EFSA rapid clearance path	D3 Reg. clarity; D2 Market	2027–2029
Bio-composites	43.2	62.8	19.6	Research clusters (NL, DE, SE)	D1 Manufacturing; D4 Infra	2029–2032
Mono-material	65.8	84.4	18.6	RecyClass design for recycling	D3 Standards; D4 MRF capacity	2026–2027

TABLE 10. SPTTI Sensitivity Analysis — Effect of +10% Dimension Score Improvement on Composite SPTTI

SP Category	Base SPTTI	Scenario A +10% D1	Scenario B +10% D4	Scenario C +10% D3	Max Gain (Best Scenario)	Most Responsive Dimension	Rank
Bio-based Polymers	56.8	59.8 (+3.0)	58.8 (+2.0)	59.3 (+2.5)	3.0	D1 Technology	5
Compostable Films	55.3	58.3 (+3.0)	57.8 (+2.5)	57.8 (+2.5)	3.0	D1/D4 (tied)	6
Recycled PET	71.8	74.8 (+3.0)	73.8 (+2.0)	74.3 (+2.5)	3.0	D1 Technology	2
Paper & Fibre-based	75.9	78.9 (+3.0)	77.9 (+2.0)	78.4 (+2.5)	3.0	D1 Technology	1
Reusable Systems	50.8	53.8 (+3.0)	53.8 (+3.0)	52.8 (+2.0)	3.0	D1/D4 (tied)	7
Active & Intelligent	46.8	49.8 (+3.0)	48.8 (+2.0)	49.3 (+2.5)	3.0	D1 Technology	8
Bio-composites	43.2	46.2 (+3.0)	45.2 (+2.0)	45.7 (+2.5)	3.0	D1 Technology	8*
Mono-material Recyclable	65.8	68.8 (+3.0)	68.3 (+2.5)	68.3 (+2.5)	3.0	D1 Technology	3

VI. DISCUSSION

A. The Technology > System Readiness Gap: Theoretical Implications

The identified and consistently observed Technology > System readiness gap across all eight SP categories can be viewed as not only an empirical finding of India but also as a theoretically important outcome. It establishes that the principal root cause of socio-technical lock-in in Indian packaging is at the regime level in the form of incumbent infrastructure, cost structures and institutional arrangements, and not at the niche level

in the development of emerging technology. Technology niche innovations (compostable films, bio-based polymers) have reached the level of technical maturity (TRL 6+) to be implemented if market, regulatory and infrastructure factors were to coordinate with the technical. The binding constraints are at the regime level: the lack of industrial composting at scale, lax EPR implementation, ambiguous BIS standards, and emerging reverse logistics. The above finding echoes the theoretical finding [50] that transitions to low-carbon in the complex sectors do not stagnate at the technology level but rather as a result of the incumbent regime and institutional inertia.

In a TIS perspective [51], [52], it is the SPTTI framework that reveals what TIS functions are weakest in each type of SP: market formation (D2) weakest in bio-based and compostable formats; legitimisation and resource mobilisation, weakest (D3) in active/intelligent packaging; weakest (D4) in compostable and reusable formats. This functional mapping directly guides the design of TIS-based policy interventions - the relevant policy lever is not generic R&D investment but specific infrastructure investment, standards development and market formation tools tuned to the particular TIS functional gap in each format category.

B. SPTTI as a Policy and Investment Prioritisation Tool

The sector-disaggregated scores of SPTTI offer practical advice to various decision-maker constituencies. The gap analysis identifies the most impactful intervention types as D4 infrastructure investment in compostable format and D3 regulatory clarification in bio-based polymers and active packaging to Indian policymakers in the packaging industry. In the case of industry associations like IIP and PIAI, the SPTTI offers evidence-based lobbying priority packaging interventions, namely: the creation of industrial composting clusters according to the PPP models, bio-polymer packaging standards development according to BIS, and guidelines on design-for-recyclability of mono-material formats. To inform individual firm investment decisions, sector-specific scores of the SPTTI (**Table VI**) can serve as an indicator of transition readiness: in the case of FMCG and e-commerce, the investments in paper/fibre-based and rPET transitions should be regarded as the signal of transition ($SPTTI \geq 70$, commercially viable), whereas the investment in bio-composite and active packaging development should be viewed as the.

C. India-EU Gap: Policy Lessons

Three policy lessons concerning priorities are identified in the India-EU SPTTI comparison. Firstly, market creation instruments such as required recycled content levels, design-for-recyclability requirements under the PPWD and eco-design regulations are the primary drivers of the superior D3 (Regulatory Readiness) scores of the EU, as opposed to direct technology subsidies. The existing regulatory strategy used by India focuses on prohibition (single-use plastic bans) rather than creating a market; a similar range of required recycled content goals and eco-design would directly enhance D3 scores and trigger the development of D2 markets. Second, the D4 infrastructure advantage of the EU is not largely a product of public investment, but of regulatory-based infrastructure development of the private sector: the deposit-return systems and EPR-funded MRF upgrades generate investible streams of revenue to infrastructure operators. To recreate this model in India would entail EPR levy collection and disbursement on a scale that has not yet been reached by the current EPR mechanism. Third, the comparatively low India-EU distance in paper/fibre-based packaging (14.9 points, converging by 2025-2026) indicates that in the situation where local production has already been established and where technology differentiation in the EU is unimportant, the Indian industry can bridge the gap in the short term with regulatory harmonisation only, without building the infrastructure needed to support compostable or reusable.

D. Methodological Contributions and Replicability

The SPTTI methodology has been created to be replicable outside of India. The four-dimensional, sixteen-sub-criterion structure, the Delphi scoring protocol, the AHP weighting process, and the normalisation process are all designed to be context-neutral; that is, only a local expert panel (minimum $n=20$) and local contextualised sub-criterion definitions are required to tailor the index to any emergent economy packaging environment. The validation protocol (correlation with survey adoption data on the industry) is also transferable. Future developments will involve a digital SPTTI calculator to package engineers, an annual SPTTI tracking dashboard to work with Indian packaging associations and cross-country comparative analysis, by applying to other emerging packaging markets, Brazil, Indonesia, Vietnam and Nigeria.

VII. CONCLUSIONS

The present paper outlines the development, validation and use of the Sustainable Packaging Technology Transition Index (SPTTI), a multi-criteria composite index that measures transition readiness in four dimensions: technology, market, regulatory, and infrastructure readiness of eight types of sustainable packaging in an Indian context. The main result is clear: Technology Readiness (D1) outperforms System Readiness (D2+D3+D4) by an average margin of 29.9 index values in all eight categories, indicating that the process of changing to sustainable packaging in India is infrastructure- and market-bound and not technology-bound.

The paper's four principal contributions are: (i) the first empirically validated TRL assessment of eight sustainable packaging categories under Indian manufacturing conditions (Delphi, $n=30$, R1 CV 8.0–23.5%, R2 CV 4.5–13.7%); (ii) an AHP-validated four-dimension, sixteen-sub-criterion SPTTI architecture with transparent, replicable weighting methodology; (iii) SPTTI composite scores and sector-level transition roadmaps demonstrating that only paper/fibre-based (75.9) and recycled PET (71.8) achieve 'Transition Ready' status under current Indian conditions; and (iv) an India–EU SPTTI gap analysis (mean gap: 19.7 points) identifying D3 regulatory and D4 infrastructure deficits—not D1 technology—as the primary drivers of India's transition lag relative to the EU PPWD framework.

The SPTTI is geared towards a replication to other emerging economy packaging markets. Its industry-specific disaggregation, open-weighting approach, and validation procedure offer a cross-border template of packaging transition assessment worldwide. Future efforts will entail the creation of an annual SPTTI monitoring system, the expansion of the framework to include packaging-intensive downstream industries (quick service restaurants, pharmaceutical blister packaging, agricultural produce packaging), and a digital decision-support system to be created by packaging engineers and policy staff of industry associations.

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