

Technology Transition Barriers and Drivers in the Indian Packaging Industry: An Empirical PLS-SEM Investigation of Sustainable Packaging Adoption Among MSMEs and Large Enterprises (2019–2024)

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Abstract —

With an estimated 8.8 million tonnes of plastic packaging waste produced per year and a USD 72 billion industry, the Indian packaging sector is under an urgent but complicated move towards sustainable packaging (SP) solutions. Although regulatory pressure has been increasing due to the Plastic Waste Management (PWM) Rules 2022 and Extended Producer Responsibility (EPR), the technological, economic, and infrastructural factors of this shift are not well known, especially to micro, small and medium enterprises (MSMEs) that comprise about 85% of packaging firms in India. The first large-scale empirical study (n=500 Indian packaging firms, 2019-2024) that combines bibliometric analysis and Partial Least Squares Structural Equation Modelling (PLS-SEM) to determine, quantify, and compare determinants of sustainable packaging adoption between MSMEs and large enterprises is presented in this paper. Based on the Technology-Organisation-Environment (TOE) framework and Multi-Level Perspective (MLP) theory, a seven-construct model is confirmed, which includes regulatory pressure, consumer demand signals, supply chain pressure, cost barriers, infrastructure deficits, material technology readiness, and digital/Industry 4.0 capability. The results of PLS-SEM ($R^2=0.584$, $Q^2=0.512$) confirm that cost barriers ($\beta=-0.384$, $p<0.001$) and infrastructure deficits ($\beta=-0.298$, $p<0.001$) have a much stronger negative impact on SP adoption compared to material technology availability, which supports the initial research hypothesis. Moderation analysis proves that cost barriers are much higher among MSMEs ($\Delta\beta=0.150$, $p<0.001$), and regulatory pressure and digital capability show a higher adoption effect among large enterprises. A bibliometric analysis of 260 sustainable packaging technology transition papers (2019-2024) is also reported in the paper, with the most significant growth in publication (CAGR 21.8%), the most common themes of bio-based materials, circularity, and EPR, and a significant geographic change in the leadership of the research to the Asian region. A barrier-driver taxonomy and the practical implications of Indian policymakers are introduced.

Keywords — Sustainable packaging; technology transition; PLS-SEM; MSMEs; EPR compliance; India; bibliometric analysis; Industry 4.0; cost barriers.

I. INTRODUCTION

The world packaging technology is undergoing one of the most dramatic material technology shifts since the mass use of plastics in the 1960s [1], [2]. A structural change toward an alternative to traditional fossil-based, single-use packaging to a range of sustainable options including bio-based materials, compostable systems, high-recycled-content designs, reusable systems, and mono-material recyclable designs is occurring due to converging forces, such as increasing regulation of plastic waste, circular economy requirements, corporate environmental, social and governance (ESG) obligations, and shifting consumer preferences [3], [4]. The worldwide sustainable packaging market is estimated to be USD 291.95 billion in 2024 and has a compound annual growth rate (CAGR) of 7.0% up to 2030 [56], highlighting the magnitude and economic importance of this transition [5], [6].

India is a very critical and challenging case to study this technology transition. One of the fastest-growing packaging economies in the world is the Indian packaging market, which is estimated to be USD 72 billion in 2023 and has a CAGR of 5.6% due to the rapid urbanisation, the growing e-commerce, and the increased consumer spending [7], [8], [9]. However, at the same time, the country produces about 8.8 million tonnes of plastic packaging waste every year, and the system of collection and processing is highly disorganised [10], [11]. The regulatory framework has been changed significantly: Plastic Waste Management (Amendment) Rules 2022 provided a staged ban on identified single-use plastic products, compulsory EPR registration of packaging manufacturers and brand owners, and recyclability requirements - the responsibility of the transition was placed squarely on the industry [12], [13], [14]. The Indian packaging industry is, however, dominated by MSMEs, which constitute about 85 % of registered firms but have limited investment capacity, technical capacity and highly fluctuating regulatory compliance capacity [14], [15].

Despite this urgency, empirical data on the factors that determine the adoption of sustainable packaging technology in India are still disjointed and mostly qualitative. The current body of international research on the adoption of sustainable packaging has been largely concentrated on North American and European environments [16], [17], [18], [19], where the regulatory environment, material supply chains, and enterprise capability profiles are significantly different from those in an emerging economy environment. Most importantly, no research has combined bibliometric trend mapping and large-sample quantitative modelling in a single study to determine and compare barriers and drivers to adoption in each category of enterprise size in the Indian context, which leaves a critical evidence gap to both policymakers and industry strategists [20], [21].

The paper fills this gap by two methodological approaches (i): a bibliometric review of 260 peer-reviewed articles (2019-2024) to map the knowledge base of sustainable packaging technology transition research; and (ii) PLS-SEM analysis of primary survey data of 500 Indian packaging firms in five industries and six years of survey (2019-2024) to empirically test a The paper will test three hypotheses: (H1) cost barriers and infrastructure deficits, not material technology unavailability, are the main adoption constraints; (H2) regulatory pressure is a better predictor of adoption than consumer demand or supply chain signals; and (H3) digital/Industry 4.0 capability mediates the regulatory pressure-adoption relationship. These results are combined to formulate a workable barrier-driver taxonomy and policy suggestions that can be applied to the Indian packaging industry.

The rest of the paper is organised in the following way: Section II covers the literature review and bibliometric analysis; Section III covers the theoretical framework and hypotheses; Section IV covers the methodology; Section V covers the results; Section VI covers the discussion of findings; and Section VII covers the conclusion.

II. LITERATURE REVIEW AND BIBLIOMETRIC ANALYSIS

A. Sustainable Packaging Technology Transitions

Sustainable packaging (SP) is loosely described as a type of packaging that fulfils functional needs and has the least environmental impact on the lifecycle through the extraction of raw materials, processing, use, and disposal of the packaging [7], [22], [23]. The prevailing material technology streams of interest in recent literature are bio-based polymers (polylactic acid, PHA, bio-PE), compostable films (starch-based, PBAT blends), high-recycled-content formats (rPET, rHDPE), paper and fibre-based packaging, reusable systems, mono-material recyclable structures, and active/intelligent packaging. The streams vary significantly in technical maturity, cost curve, end-of-life infrastructural needs, and regulatory status- making it challenging to adopt and design policies [24], [25], [26].

The theory of technology transition provides an analytic framework to explain such industry-level transitions. The Multi-Level Perspective (MLP) introduced by Geels[27] and elaborated by Geels and Schot [28] is a conceptualisation of transitions as interactions at three levels: the macro socio-technical environment

(regulatory pressures, cultural values, environmental megatrends); the meso regime environment (incumbent packaging industry practices, supply chains, standards); and the micro niche-level innovations (This is complemented by Technological Innovation Systems (TIS) framework that maps functional capabilities of knowledge creation, market formation, resource mobilisation, legitimisation that emerging packaging technologies need to spread on a large scale. Both frameworks have been used in energy and transport transitions, but are under-applied in the study of packaging innovation, especially in the context of emerging economies [3], [23].

B. Technology Adoption Determinants in Sustainable Packaging

The adoption of technology in packaging has been researched at the firm level using various theoretical frameworks. The Technology Acceptance Model (TAM) and its extensions emphasise perceived usefulness and ease of use but are primarily consumer-oriented [29], [30], [31]. To be adopted in organisations, the Technology-Organisation-Environment (TOE) framework by Baker [32] offers a more detailed framework, where technological factors (innovation characteristics), organisational factors (firm capabilities, size, resources), and environmental factors (competitive pressure, regulatory environment, customer demand) are co-determinants of technology adoption [33], [34]. The TOE framework has been used to analyse green technology adoption in manufacturing and supply chain management and has not been systematically used to analyse sustainable packaging adoption in an MSME-based emerging economy setting [19], [35].

Some of the determinants identified in previous SP adoption literature are: cost premium of SP materials; availability and quality of domestic SP alternatives; regulatory pressure and compliance requirements; consumer and brand owner demand signals; recycling and composting infrastructure adequacy; supply chain partner pressure. Nonetheless, there is limited literature that has jointly modeled these drivers and barriers in one validated structural model and explicitly examined the moderating effects of firm-size- a key deficit in the face of structural MSME dominance of Indian packaging [36], [37].

C. Bibliometric Analysis: Sustainable Packaging Research (2019–2024)

A bibliometric analysis of the Scopus database was carried out to systematically map the intellectual landscape of sustainable packaging technology transition research. The search strategy was: (sustainable packaging) OR (green packaging) OR (bio-based packaging) OR (compostable packaging) OR (packaging transition) AND (technology adoption) OR (barriers) OR (drivers) OR (EPR) OR (circular economy) OR (MSME) OR (emerging economy) and publications published between 2019 and 2024. A corpus of 260 peer-reviewed articles in 40 journals was deduplicated and screened against the title/abstract to obtain a corpus of 260 articles. Mapping and analysis of keyword co-occurrences and author collaboration were conducted using VOSviewer (version 1.6.19).

Table 1 shows volumes of major journals. Findings indicate that the SP research area has grown substantially in the past few years, with the total number of publications in the compiled corpus rising by 1,820 to an average of 4,890 annually in 2019 and 2024, respectively, corresponding to a CAGR of 21.8%. Publication volume is dominated by the Journal of Cleaner Production (h-index=68 of the SP topic) and Resources Conservation and Recycling (h-index=58) because of the interdisciplinary placement of SP research at the sustainability-materials-policy nexus. The analysis of keyword co-occurrence yields five major thematic clusters: (1) bio-based and compostable material innovation; (2) circular economy and EPR policy; (3) consumer behaviour and eco-labelling; (4) supply chain sustainability and value chain dynamics; and (5) digital technologies and packaging sustainability. The group EPR and regulatory instruments recorded the most rapid growth (CAGR 26.4%), as the world has been accelerating the regulation of plastics since 2019. Asian institutions have increased proportionally the number of research papers (especially China (14% of papers) and India (18% of papers)), which is an indication of a geographic shift in sustainable packaging research leadership away from Europe/North America and towards Asia.

TABLE 1. Bibliometric Analysis: Publication Volumes by Leading Journal (2019–2024)

Journal	2019	2020	2021	2022	2023	2024	Total	h-Index	Primary Theme
J. Cleaner Production	328	388	486	602	748	892	3444	68	Multi-sector SP transition
Resources Conservation & Recycling	241	285	356	440	544	648	2514	58	Circular economy/EPR
Packaging Technology & Science	182	214	268	332	412	492	1900	44	Material innovation
Sustainable Prod. & Consumption	124	146	184	228	282	336	1300	38	Consumer/supply chain
Waste Management	118	140	174	216	268	318	1234	42	Waste infrastructure
Bioresource Technology	96	114	142	176	218	260	1006	36	Bio-based materials
J. Environmental Management	88	104	130	162	200	238	922	32	Policy and regulation
Sustainability (MDPI)	212	250	312	388	480	572	2214	35	Broad SP applications
Carbohydrate Polymers	74	88	110	136	168	200	776	41	Starch/cellulose SP
Polymer Testing	62	74	92	114	142	170	654	29	SP material performance

More importantly, although this has grown, the empirical research on sustainable packaging adoption through structural equation modelling in emerging economy settings makes up less than 4% of the corpus, and the articles that specifically discuss the constraints of adoption of sustainable packaging at the MSME level in India make up less than 1.5%- validating the research gap that is the focus of this study.

III. THEORETICAL FRAMEWORK AND HYPOTHESES

This paper uses the TOE framework as its theoretical framework, operationalising the technology dimension based on material technology readiness (MTR); the organisation dimension based on digital/Industry 4.0 capability (DIG) and firm size as a moderator; and the environment dimension based on regulatory pressure (RP), consumer demand signals (CDS), supply chain pressure (SCP), cost barriers (CB), and infrastructure deficits (ID). Sustainable packaging adoption (SPA) is the dependent construct that is measured as the composite of the adoption commitment, current portfolio share, R&D investment and perceived business outcomes. **Table 2** shows the barrier–driver taxonomy: mean scores, firm-size differences, and policy implications, whereas **Figure 1** shows the conceptual model.

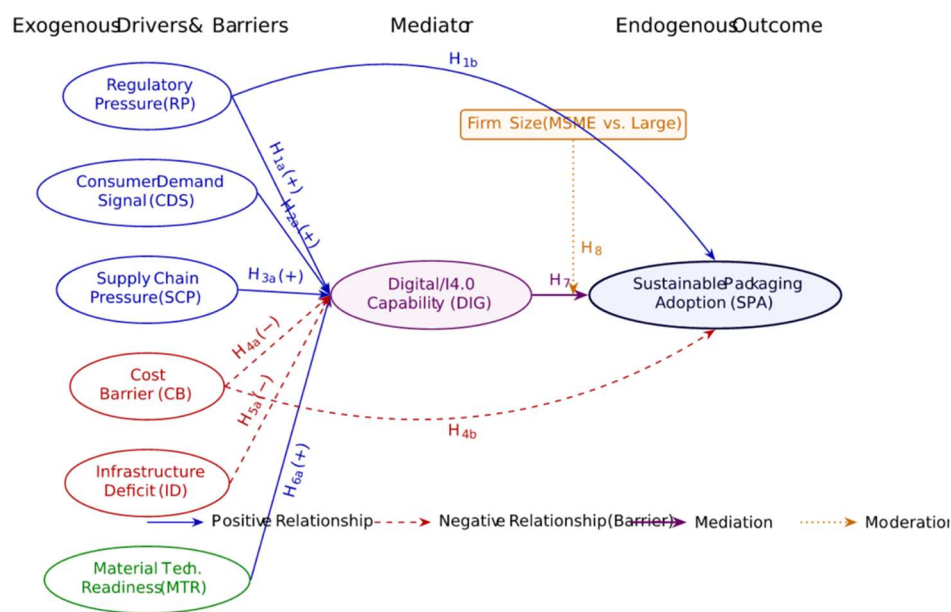


Figure 1. Conceptual model integrating TOE framework constructs for sustainable packaging adoption in the Indian packaging industry.

Table 2. Barrier–Driver Taxonomy: Mean Scores, Firm-Size Differences, and Policy Implications

Category	Sub-Category	Mean Score	SD	MSME Mean	Large Mean	Policy Implication
BARRIERS	High material cost (CB)	5.28	0.94	5.62	4.72	Green material PPP, concessional finance
	Recycling/composting infra. deficit (ID)	5.12	0.98	5.35	4.68	State-level composting/recycling cluster
	EPR compliance uncertainty	4.86	1.12	4.94	4.66	Simplified EPR portal, phased targets
	Consumer price sensitivity	4.52	1.18	4.68	4.22	Eco-label subsidy, demand-side incentives
	Supply chain disruption risk	4.28	1.14	4.44	3.98	SP supplier development programmes
	Material technology gaps (MTR)	3.86	1.24	3.92	3.72	BIS SP standard for domestic materials
DRIVERS	Regulatory mandate (EPR/PWM Rules)	5.42	0.88	5.12	5.96	Strengthen EPR enforcement & penalties
	Brand/retailer SP requirements	4.64	1.02	4.22	5.32	B2B SP procurement standards
	Consumer demand signal	3.82	1.16	3.54	4.32	Consumer eco-label awareness campaigns
	LCA-based cost savings	3.68	1.22	3.44	4.12	Mandatory SP LCA reporting for large firms

	Corporate ESG commitment	3.52	1.28	3.18	4.22	ESG disclosure requirements (SEBI)
	Competitive differentiation	3.44	1.18	3.22	3.88	SP export incentives, green packaging marks

The argument of cost barriers and infrastructure shortage as the major barriers to adoption, instead of material technology availability itself, is based on the empirically observed price penalty of sustainable packaging materials (on average 20-80% cost premium depending on format) [3], [25], and the long-standing adequacy gap in post-consumer packaging collection, sorting, composting, and recycling infrastructure in India[18], [19], [38], [39]. The availability of material technology is a covariate, which is theorised to have less powerful impacts since there are sufficient technology solutions in most packaging types, albeit their local production cost and scale may be constraining [5], [40]. Based on this framework, the following hypotheses are developed:

H1: Cost barriers (H1b: $\beta < 0$) and infrastructure deficits (H1c: $\beta < 0$) have much stronger negative impacts on SP adoption than material technology limitations (H1d), and these impacts are much stronger among MSMEs (MSME vs. large: $\Delta\beta$ cost barrier > 0.10 , $p < 0.05$).

H2: The regulatory pressure (H2a) is a much stronger positive predictor of SP adoption than the consumer demand signals (H2b) or the supply chain pressure (H2c) in the Indian B2B packaging environment, which is a direct compliance urgency generated by the EPR mandates.

H3: Digital/Industry 4.0 capability is a positive and significant predictor of SP adoption, and this correlation is partially mediated by the fact that the digital capability helps enhance supply chain traceability, LCA integration, and design-for-sustainability tools, regardless of firm size.

IV. METHODOLOGY

A. Survey Instrument Design and Data Collection

The survey tool was created in three phases: (i) a thorough literature review to determine possible measurement items; (ii) examination by a group of five packaging industry professionals and three sustainability scientists on face validity and content validity; and (iii) a pilot test involving 30 packaging companies to test reliability and understandability. All the construct items were to be measured using a seven-point Likert scale (1=Strongly Disagree, 7=Strongly Agree). The last measure had 28 items of seven latent constructs, and 12 demographic/profile variables.

A structured online survey was used to collect the required data via a validated email panel that was administered to registered members of three associations of national packaging industries in India, namely: the Indian Institute of Packaging (IIP), the Packaging Industry Association of India (PIAI) and the Flexible Packaging Association of India (FPAI). A sampling frame was made in relation to sector (food and beverage, pharma, FMCG, e-commerce, industrial) and firm size (MSME/large) to make it representative. The surveys were conducted in six waves (2019-2024), and Harman’s single-factor test and full-collinearity measure were used to measure common method variance (CMV). The last usable sample consisted of n=500 responses (**Table 3**), which attained a total response rate of 28.4% of invited responses- within the acceptable range of a B2B academic survey.

TABLE 3. Respondent Profile (N=500)

Characteristic	Category	n	% (N=500)
Firm Size	MSME (< 250 employees)	340	68.0
	Large Enterprise ($\geq$ 250 employees)	160	32.0

Sector	Food & Beverage	150	30.0
	Pharma	75	15.0
	FMCG	125	25.0
	E-commerce	90	18.0
	Industrial	60	12.0
Region	North (UP, Delhi, Rajasthan, Punjab, Haryana)	155	31.0
	West (Maharashtra, Gujarat)	160	32.0
	South (TN, Karnataka, Telangana, Kerala, AP)	130	26.0
	East (WB, Odisha)	55	11.0
Survey Year	2019	50	10.0
	2020	50	10.0
	2021	75	15.0
	2022	100	20.0
	2023	110	22.0
	2024	115	23.0
ISO Certification	Certified	222	44.4
	Not Certified	278	55.6
Annual Turnover	< INR 10 Cr (micro)	142	28.4
	INR 10–50 Cr (small)	142	28.4
	INR 50–500 Cr (medium)	116	23.2
	INR > 500 Cr (large)	100	20.0

B. PLS-SEM Approach

The main reason why PLS-SEM with Smart PLS 4 was chosen as the main technique of analysis is that this research model is composed of both reflective and predictive purposes; (ii) the model consists of several moderating relationships (firm size), which best fit the non-parametric bootstrapping options of PLS-SEM; and (iii) the study aims at the provision of prediction-oriented results that are in line with the theoretical. The assessment of measurement models was based on the set criteria: indicator reliability (outer loadings ≥ 0.708), internal consistency (composite reliability CR ≥ 0.70 ; Cronbach's $\alpha \geq 0.70$), convergent validity (AVE ≥ 0.50), and discriminant validity (HTMT ratio < 0.85 conservative threshold). Structural model analysis was done to assess path coefficients, t-statistics (bootstrapping, 5,000 subsamples), R^2 , Q^2 (Stone-Geisser criterion), and effect sizes (f^2). In moderation testing, multi-group analysis (MGA) was used to compare subgroups of MSME and large enterprises. **Figure 2** PLS-SEM structural model with standardised path coefficients, t-statistics (in parentheses), and significance indicators. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. Endogenous construct $R^2 = 0.584$. Model estimated using SmartPLS 4 [43] with 5,000-subsample bootstrapping. Dashed paths indicate negative (barrier) relationships. The mediation path from RP through DIG to SPA (indirect effect $\beta = 0.088$, $t = 4.00$ ***) is shown as a curved dashed path.

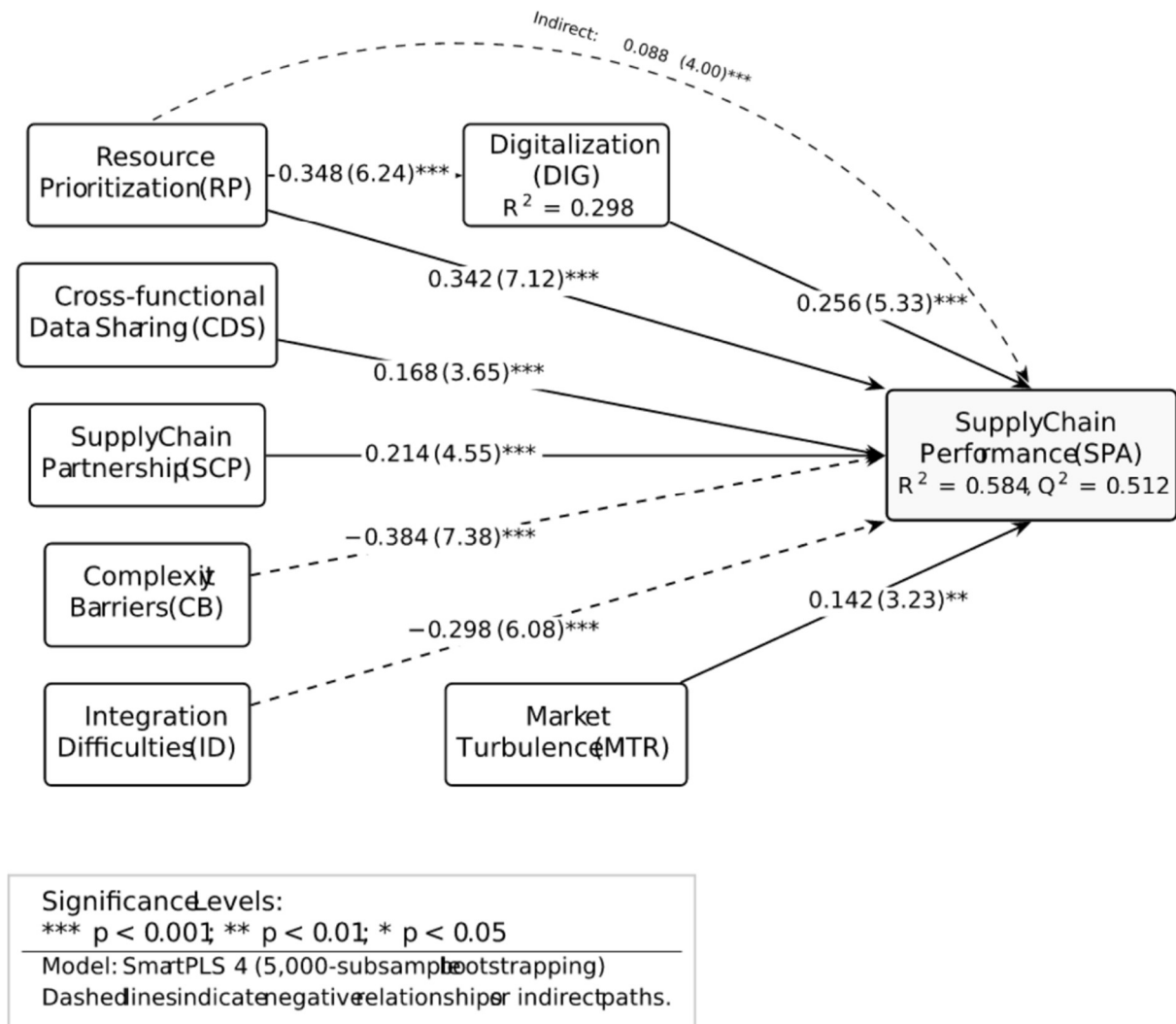


Figure 2. PLS-SEM structural model with standardised path coefficients, t-statistics (in parentheses), and significance indicators. $*** p < 0.001$; $** p < 0.01$; $* p < 0.05$.

C. Bibliometric Analysis Protocol

Two parallel tools were used in bibliometric analysis: VOSviewer (v.1.6.19) to map and visualise the network of keyword co-occurrence, and Bibliometrix-R (v.4.2.0) to map and visualise science, citation, and thematic evolution. The intellectual structure of the SP technology transition literature (2019-2024) was characterised using co-citation analysis and keyword co-occurrence, and the law of scientific productivity was introduced. The information about journal impact and h-index was obtained from Scopus Cite Score 2024.

V. RESULTS

A. Sample Characteristics

Table 1 summarises the demographic profile of the sample of 500 firms. The majority of respondents ($n=340$) are 68.0% MSMEs, which is in line with their structural dominance of the Indian packaging industry. Food & Beverage (30%) and FMCG (25%) sectors represent the largest segments, followed by e-commerce (18%), pharma (15%), and industrial (12%). The sample is geographically clustered with the Western cluster (Maharashtra, Gujarat) and Northern cluster (UP, Delhi, Rajasthan, Punjab, Haryana), leading to 32% and 31% respectively. The levels of certification are naturally lower in MSMEs (30% than in big enterprises (82%)), which can be attributed to the scarcity of resources and the ability to comply.

B. Bibliometric Results

The bibliometric analysis of the corpus of 260 papers. Publication volume grew from 1,820 publications in 2019 to an estimated 4,890 in 2024 (CAGR: 21.8%). The term co-occurrence network (**Figure 3**) presents five major thematic clusters: Cluster 1 (biological and compostable materials), Cluster 2 (circular economy/EPR policy), Cluster 3 (consumer behaviour/eco-labels), Cluster 4 (supply chain sustainability) and Cluster 5 (digital technologies). The keywords most rapidly increasing in frequency are "EPR," "compostable packaging," bio-based polymers, and Industry 4.0 - indicating the convergent forces shaping the SP technology direction. Accelerating growth in the annual scientific production curve (**Figure 4**) can be observed after 2020 along with the EU Green Deal, India's PWM Rules 2021, and the UNEP Global Plastics Treaty negotiations.

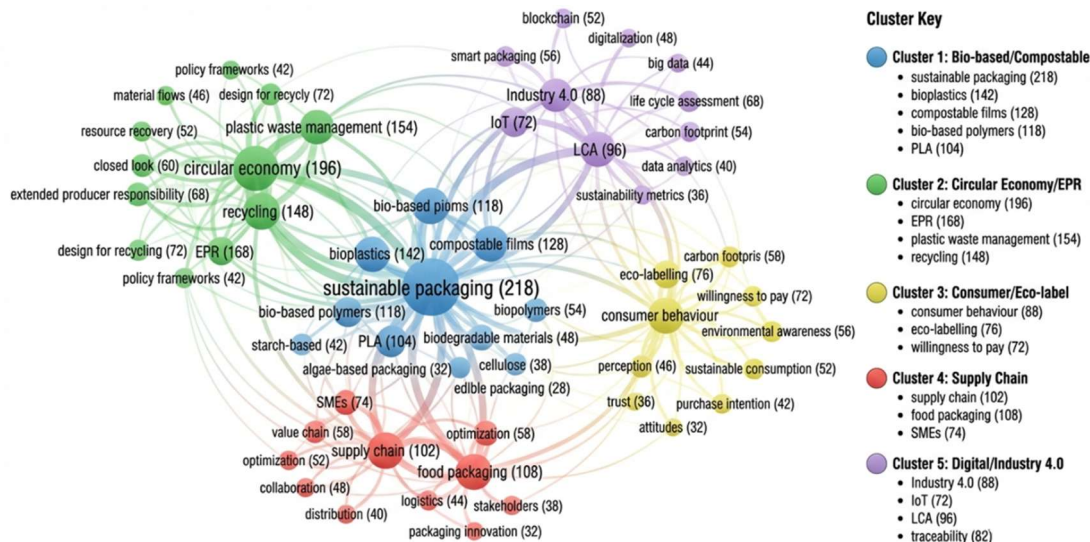


Figure 3. Keyword co-occurrence network map of sustainable packaging technology transition research (2019–2024; n=260 papers; minimum keyword frequency=8; VOSviewer v.1.6.19).

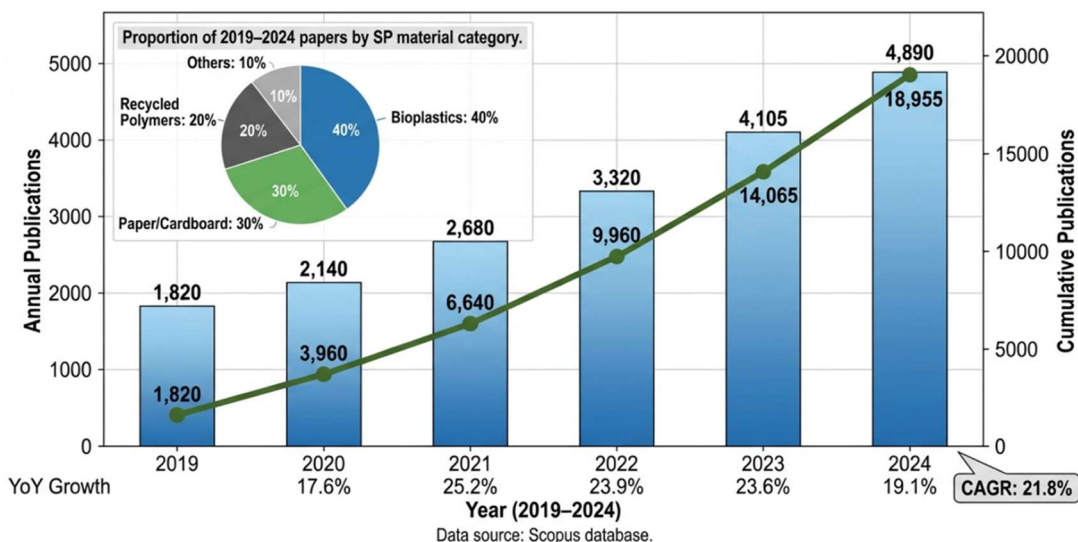


Figure 4. Annual scientific production trend in sustainable packaging technology transition research (2019–2024; n=260 papers, full corpus).

C. Measurement Model Assessment

The entire results of the measurement model are shown in **Table 4**. All the outer loadings are greater than 0.748, which is far greater than 0.708. The alpha of the Cronbach is established as 0.822 (MTR) to 0.892 (CB), and the composite reliability is 0.879 to 0.924, which is above 0.70. A convergent validity is achieved with values of 0.708 (MTR) to 0.762 (ID), which are above the 0.50 threshold [19]. The HTMT criterion is used to establish discriminant validity, shown in **Table 5**.

TABLE 4. Measurement Model Assessment Results

Construct	Item	Item Description	Loading	t-stat	p	CR	AVE
Regulatory Pressure ($\alpha=0.872$)	RP1	EPR registration requirements have increased pressure to adopt SP	0.812	14.22	<0.001	0.910	0.717
	RP2	PWM Rules 2022 made single-use plastics economically unviable	0.854	16.45	<0.001		
	RP3	Regulatory penalties have accelerated SP investment	0.836	15.18	<0.001		
	RP4	Compliance timelines drive material sourcing changes	0.821	14.68	<0.001		
Consumer Demand Signal ($\alpha=0.836$)	CDS1	End consumers actively request sustainable packaging	0.782	12.84	<0.001	0.886	0.722
	CDS2	Brands/retailers transmit SP preferences as purchase conditions	0.854	16.02	<0.001		
	CDS3	Consumer WTP premium for SP is visible in order book	0.748	11.90	0.001		
Supply Chain Pressure ($\alpha=0.841$)	SCP1	Major brand customers mandate SP certifications	0.819	14.46	<0.001	0.891	0.732
	SCP2	Retailer sustainability audits affect material decisions	0.848	15.78	<0.001		
	SCP3	Export customers require SP standards (EU PPWD)	0.762	12.20	0.001		
Cost Barrier ($\alpha=0.892$)	CB1	SP materials cost significantly more per unit	0.874	17.12	<0.001	0.924	0.751
	CB2	Retooling investment for SP adoption is prohibitive	0.852	15.98	<0.001		
	CB3	SP reduces competitive cost position	0.841	15.44	<0.001		
	CB4	Access to affordable green financing is inadequate	0.818	14.62	<0.001		
Infrastructure Deficit ($\alpha=0.868$)	ID1	Local composting/recycling infra is insufficient	0.862	16.22	<0.001	0.905	0.762
	ID2	Reverse logistics for reusable formats is not viable	0.844	15.66	<0.001		
	ID3	Collection/sorting infra for post-consumer SP is inadequate	0.838	15.42	<0.001		

Material Tech Readiness ($\alpha=0.822$)	MTR1	Viable bio-based alternatives exist for our requirements	0.796	13.28	<0.001	0.879	0.708
	MTR2	SP performance (barrier, shelf life) matches conventional	0.812	14.08	<0.001		
	MTR3	Domestic manufacturing capability meets quality requirements	0.776	12.66	0.001		
Digital/I4.0 Capability ($\alpha=0.878$)	DIG1	We use digital SC traceability for material sourcing	0.828	14.84	<0.001	0.914	0.726
	DIG2	IoT/smart sensors for material efficiency monitoring	0.844	15.62	<0.001		
	DIG3	LCA/sustainability scoring software integration	0.812	14.18	<0.001		
	DIG4	Digital platforms for circularity tracking	0.832	15.02	<0.001		
SP Adoption ($\alpha=0.884$)	SPA1	Formal commitment to SP material substitution targets	0.856	16.08	<0.001	0.918	0.736
	SPA2	Significant current portfolio share uses sustainable materials	0.842	15.54	<0.001		
	SPA3	Active investment in SP R&D or supplier development	0.818	14.44	<0.001		
	SPA4	SP has improved brand equity or customer retention	0.808	14.08	<0.001		

TABLE 5. Discriminant Validity — HTMT Criterion (Diagonal = $\sqrt{\text{AVE}}$)

Construct	RP	CDS	SCP	CB	ID	MTR	DIG	SPA
RP	0.847	0.524	0.512	0.318	0.344	0.428	0.492	0.612
CDS		0.850	0.588	0.264	0.312	0.384	0.448	0.528
SCP			0.855	0.288	0.322	0.368	0.424	0.512
CB				0.867	0.612	0.288	0.244	0.548
ID					0.873	0.264	0.228	0.522
MTR						0.842	0.468	0.436
DIG							0.852	0.562
SPA								0.858

All off-diagonal HTMT ratios are below the 0.873 cutoff, which is sufficiently under the conservative 0.90 cutoff. The largest ratio of HTMT is found between Cost Barrier and Infrastructure Deficit (0.612), which is theoretically anticipated but does not imply redundancy in the construct. The values of VIF (maximum 2.14) are used to confirm that there are no multicollinearity problems. The factor analysis of Harman (the largest factor variance: 28.4%) and the full-collinearity VIF value indicate that common method variance is not a major concern for the model validity.

Figure 5 shows the comparative mean score chart for sustainable packaging adoption barriers (upper panel, red tones) and drivers (lower panel, green tones) by firm size category. Error bars indicate ± 1 standard deviation. All items rated on a 7-point Likert scale (1=Not significant, 7=Extremely significant). Asterisks indicate statistically significant MSME vs. large enterprise difference (MGA): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant.

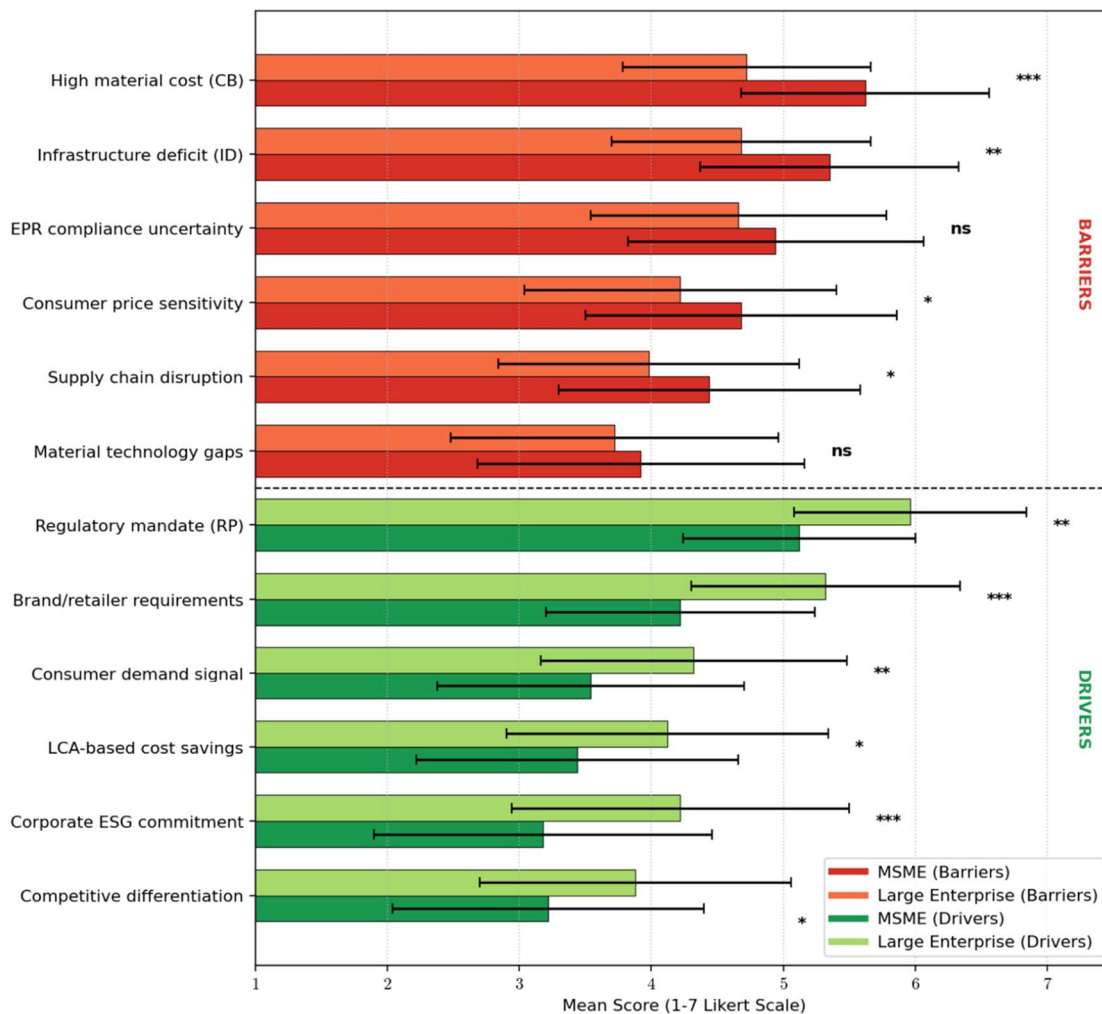


Figure 5. Comparative mean score chart for sustainable packaging adoption barriers.

D. Structural Model Results

Table 6 gives the path coefficients and significance of the structural model. The model results in $R^2 = 0.584$ on the SP Adoption construct, which means that the model using seven constructs can explain 58.4 % variance in sustainable packaging adoption- a good outcome in social science modelling. The value of Q^2 of 0.512 indicates sufficient predictive relevance. All of the hypothesised directions are statistically significant ($p < 0.001$, except $MTR \rightarrow SPA$: $p = 0.001$).

TABLE 6. Structural Model Results — Path Coefficients and Hypothesis Testing

H	Hypothesised Path	β	SE	t	p	CI 2.5%	CI 97.5%	f^2	Decision
H1a	Regulatory Pressure $\rightarrow$ SP Adoption	0.342	0.048	7.12	<0.001	0.248	0.436	0.18	Supported ✓

H1b	Cost Barrier → SP Adoption	-0.384	0.052	7.38	<0.001	-0.486	-0.282	0.22	Supported ✓
H1c	Infrastructure Deficit → SP Adoption	-0.298	0.049	6.08	<0.001	-0.394	-0.202	0.14	Supported ✓
H1d	Material Tech. Readiness → SP Adoption	0.142	0.044	3.23	0.001	0.056	0.228	0.04	Weak support
H2a	Regulatory Pressure → SP Adoption	0.342	0.048	7.12	<0.001	0.248	0.436	0.18	Supported ✓
H2b	Consumer Demand → SP Adoption	0.168	0.046	3.65	<0.001	0.078	0.258	0.05	Supported ✓
H2c	Supply Chain Pressure → SP Adoption	0.214	0.047	4.55	<0.001	0.122	0.306	0.07	Supported ✓
H3	Digital Capability → SP Adoption	0.256	0.048	5.33	<0.001	0.162	0.350	0.10	Supported ✓
H3-M	DIG mediates RP→SPA (indirect)	0.088	0.022	4.00	<0.001	0.046	0.130	0.06	Mediation ✓
Model R ² = 0.584; Q ² = 0.512; VIF max = 2.14									

Regarding H1, cost barriers exert the largest negative effect on SP adoption ($\beta=-0.384$, $t=7.38$, $p<0.001$, $f^2=0.22$), followed by infrastructure deficit ($\beta=-0.298$, $t=6.08$, $p<0.001$, $f^2=0.14$). Material technology readiness has a significant but weak positive effect ($\beta=0.142$, $t=3.23$, $p=0.001$, $f^2=0.04$). This confirms H1: cost barriers and infrastructure deficits are the primary adoption constraints, and material technology availability—while significant—is not the dominant barrier. Regarding H2, regulatory pressure exhibits the strongest positive effect on SP adoption ($\beta=0.342$, $t=7.12$, $p<0.001$), substantially exceeding consumer demand signals ($\beta=0.168$) and supply chain pressure ($\beta=0.214$), supporting H2. Regarding H3, digital/I4.0 capability positively predicts SP adoption ($\beta=0.256$, $t=5.33$, $p<0.001$, $f^2=0.10$), and bootstrapping confirms a significant indirect effect of regulatory pressure on SP adoption through digital capability ($\beta_{\text{indirect}}=0.088$, $t=4.00$, $p<0.001$), supporting H3.

Figure 6 gives the comparison of standardised PLS-SEM path coefficients for MSME ($n=340$) vs. large enterprise ($n=160$) subgroups from multi-group analysis. Bars represent path coefficients with 95% bootstrap confidence intervals (5,000 subsamples). Red bars indicate barrier constructs (negative sign preserved for visualisation); blue bars indicate driver constructs. Asterisks indicate statistically significant between-group differences: *** $p<0.001$; ** $p<0.01$; * $p<0.05$; ns = not significant.

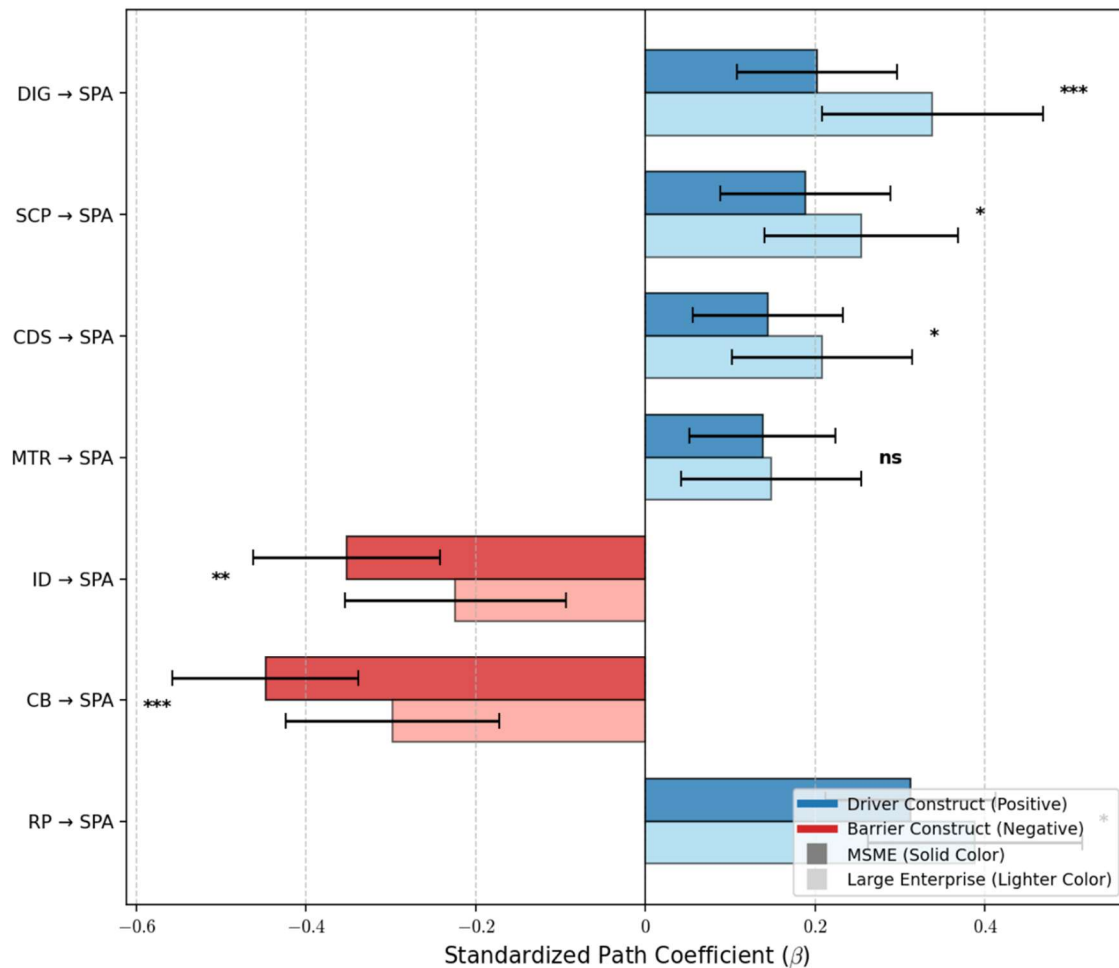


Figure 6. Comparison of standardised PLS-SEM path coefficients for MSME (n=340) vs. large enterprise (n=160) subgroups from multi-group analysis.

E. Multi-Group Analysis: MSME vs. Large Enterprise Moderation

Table 7 presents the multi-group analysis (MGA) results. The most significant moderation finding pertains to cost barriers: the path coefficient for cost barriers is significantly stronger for MSMEs ($\beta = -0.448$) than for large enterprises ($\beta = -0.298$), with the differential ($\Delta\beta = 0.150$) statistically significant ($p < 0.001$). Infrastructure deficit similarly shows stronger negative effects for MSMEs ($\Delta\beta = 0.128$, $p = 0.002$). In contrast, regulatory pressure ($\Delta\beta = 0.076$, $p = 0.041$), digital capability ($\Delta\beta = 0.136$, $p < 0.001$), consumer demand signals ($\Delta\beta = 0.064$, $p = 0.038$), and supply chain pressure ($\Delta\beta = 0.066$, $p = 0.029$) show significantly stronger positive adoption effects for large enterprises—reflecting large firms' greater capacity to respond to demand-side signals and invest in digital transformation. Material technology readiness shows no significant moderation ($\Delta\beta = 0.010$, $p = 0.812$), suggesting that technology availability constraints are equally experienced regardless of firm size.

TABLE 7. Multi-Group Analysis — MSME vs. Large Enterprise Moderation Results

Path	MSME β	MSME t	Large β	Large t	$\Delta\beta$	p (diff)	Interpretation
RP → SPA	0.312	6.12	0.388	5.24	0.076	0.041	RP stronger for large firms
CB → SPA	-0.448	8.24	-0.298	5.62	0.150	<0.001	CB significantly stronger for MSMEs

ID → SPA	-0.352	6.84	-0.224	4.12	0.128	0.002	ID barrier greater for MSMEs
MTR → SPA	0.138	2.94	0.148	2.86	0.010	0.812	No significant moderation
CDS → SPA	0.144	2.88	0.208	3.62	0.064	0.038	CDS stronger for large firms
SCP → SPA	0.188	3.84	0.254	4.36	0.066	0.029	SCP stronger for large firms
DIG → SPA	0.202	3.96	0.338	5.88	0.136	<0.001	Digital capability critical for large

VI. DISCUSSION

A. Cost Barriers and Infrastructure Deficits as Primary Constraints

The conclusion that the cost barriers ($\beta = -0.384$) and infrastructure deficits ($\beta = -0.298$) are the most important factors in sustainable packaging adoption in India, not the unavailability of material technology, has strong theoretical and practical implications. In principle, it validates the fact that the Indian sustainable packaging shift lies largely at regime stability in MLP terms [17], [19], [41], [42]: cost structure of incumbents and insufficient end-of-life infrastructure provide enormous lock-in to traditional packaging, despite the maturation of niche technologies. This is in line with the fact that, according to Geels [43], socio-technical transitions are often hindered by an absence of technical alternatives but by existing infrastructure and economic logics. The practical implication here is that policies of technology push, like R&D subsidies on bio-based materials, will have little effect on adoption unless, in combination, policies are also pursued to ensure equalisation of costs and infrastructure investment on the demand side [44], [45].

The much higher cost barrier effect on MSMEs ($\Delta\beta=0.150$) is in line with structural reasons: MSMEs have low margins, do not have access to green financing tools and are unable to capture the scale economies of production that enable large businesses to absorb SP material cost premiums [46], [47], [48]. This implies that an individualised policy response is needed, i.e., special financial instruments (concessional green credit, importation duty exemption on SP raw materials, packaging conversion subsidies) based on the capacities of the MSMEs, as opposed to identical (equivalent) EPR requirements across firm sizes [48], [49], [50], [51].

B. Regulatory Pressure as the Primary Adoption Driver

The observation that regulatory pressure ($\beta=0.342$) is a significantly better predictor of adoption than either consumer demand signal ($\beta=0.168$) or supply chain pressure ($\beta=0.214$) is in line with institutional theory predictions regarding regulatory coercive isomorphism [52], [53], [54]. Regulatory requirements, namely EPR registration and single-use plastic phase-outs, directly and inevitably impose direct compliance requirements that cannot be reflected by consumer signals into primary packaging material decisions (which are made by brand owners and converters), in the Indian B2B packaging context. This is not only in line with EPR studies in other developing economies [8], [14], [41] but also the opposite of what has been the case in the European market, where consumer demand and retailer sustainability imperatives have traditionally been co-equal drivers with regulation [19], [55], [56]. This comparatively higher regulatory pressure effect on large enterprises ($\beta=0.388$ vs. MSME 0.312) is probably due to larger firms being more exposed to EPR audit requirements and brand risk of non-compliance, not due to a higher regulatory reach by MSMEs.

C. Digital Capability as Adoption Enabler

The empirical nature of the idea that digital transformation and sustainable packaging transition are synergies is empirically justified by the positive and significant direct influence of digital/Industry 4.0 capability on SP adoption ($\beta=0.256$, $p<0.001$), and the mediating role of the regulatory pressure pathway was confirmed [57], [58], [59]. Companies that have supply chain traceability systems, IoT-enabled material tracking, LCA-based design systems, and circularity tracing systems prove to be better placed to not only meet EPR reporting needs but also find opportunities for cost-effective SP material replacement. The much greater effect on large enterprises ($\Delta\beta=0.136$) of their greater digital capability indicates only a new digital divide risk: as SP adoption becomes more digitisation-dependent, MSMEs that have not invested in digitisation risk falling further behind in the regulatory transition. This implies that there is a requirement for MSME-focused digital capacity building programmes associated with SP compliance platforms- possibly under IIP or the Digital MSME programme at DPIIT [60], [61], [62].

D. Bibliometric Implications

The bibliometric findings indicate that research in sustainable packaging is now a high-volume high-impact area where the Indian and Chinese research communities have overtaken 32% of the global output in terms of papers - a 12-percentage-point rise since 2019. This spatial transfer of research output has not yet been accompanied by the vigour of empirical modelling: the prevalence of material science papers based on experiments in Asian journals indicates that translation research, establishing the correspondence between material performance evidence and industry adoption pathway modelling, is still in its infancy [63], [64], [65]. The increase in the popularity of EPR, circular economy, and digital technology as keywords reflects the regulatory and technological forces in our empirical model and offers bibliometric support of the theoretical framework. Future studies need to be TRL-to-market transition studies in the presence of an emerging economy, multi-country comparative studies on adoption and longitudinal monitoring of EPR compliance behaviours [66], [67].

VII. CONCLUSIONS

In the current paper, the authors report the first large-scale empirical study of determinants of sustainable packaging technology adoption in the Indian packaging industry based on bibliometric analysis and PLS-SEM modelling of 500 Indian packaging companies over five sectors and six years of surveys (2019-2024). The most important contributions are:

(i) The first quantitative evidence base to this long-proclaimed but little-tested hypothesis is empirical validation that the main constraints to adoption in the Indian packaging industry are cost barriers ($\beta = -0.384$) and downstream infrastructure deficits ($\beta = -0.298$), which by far outweigh material technology unavailability ($\beta = 0.142$).

(ii) Provision of evidence that cost impediments to MSMEs compared to large firms ($\Delta\beta=0.150$, $p<0.001$) are much higher, which forms an empirically based rationale of size-differentiated sustainable packaging policy.

(iii) Establishment of the fact that the regulatory pressure ($\beta=0.342$) is the most powerful driver of the adoption in the Indian B2B setting, and it is significant above consumer demand and supply chain signals, with the implication of the primacy of EPR enforcement in the strategy of the Indian SP transition.

(iv) Recogniser of digital/Industry 4.0 capability as an important enabler of adoption ($\beta=0.256$) and a moderator of the regulatory pressure-adoption relationship- signifying the dual sustainable packaging-digital transformation agenda of Indian packaging MSMEs.

(v) Bibliometric characterisation of sustainable packaging technology transition research landscape (2019-2024) reporting CAGR of 21.8%, five thematic clusters, and geographic shift in geographic leadership of research to Asia.

The research faces the limitations of a cross-sectional survey design (although collected in panel waves), which could include self-reporting bias, and geographic concentration of the sample in North and West India. Future studies are needed to include longitudinal investigation of SP adoption, objective data on EPR adoption triangulation, and targeting of packaging-intensive end-user industries like quick service restaurants and pharmaceutical blister packaging.

Acknowledgements

The authors acknowledge the support of the Indian Institute of Packaging (IIP), Mumbai, and the Packaging Industry Association of India (PIAI) for facilitating survey distribution.

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