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ORIGINAL PAPER

Transition to Circular Plastic Economy: How It Is Unfolding in Developing Countries

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Abstract
Using a multidimensional transition framework, this paper focuses on mapping comparative progress towards the circular plastic economy (CPE) in three Asian developing countries - India, Indonesia, and Thailand. The state of the CPE system at various points in time is assessed using seven functions defining the dynamics and performance of the CPE system. Multiple lines of evidence: trade database, national policy documents, reports, academic literature, ministerial announcements, and news in mass media show 'circularity' per se is gaining high attention in recent years in the context of climate action, plastics, decent jobs, and social justice. However, groundwork in these countries started through disjoint but various actions towards plastic and waste management, characterized by the Reuse, Reduce, and Recycle principles since the 1990s. In 2017, when China imposed restrictions on waste imports, the Southeast and South Asian regions started gaining importance in the global plastic waste trade. This triggered the *Early Adoption phase* of circularity initiatives in the region through recycling, technology, and knowledge development. However, our analysis indicates that societal readiness through businesses, markets, and consumer response is still lagging. Further, policy implementation and financial mobilization also need more attention. None of the countries excel in all dimensions. While Thailand is leading, followed by India and Indonesia, but to foster just transitions to circularity, there must be holistic planning that is tailored to the contexts of the country. These include, but are not limited to, incentives for businesses, regulation, infrastructure, monitoring, evaluation, mobilization of personnel, and financial resources, and promoting community and individual awareness and action.

Keywords UNEA-5.2 Global Plastic Treaty · Global trade in wastes · Circular economy · Plastic waste management · Equity and justice in transition · Global South, sustainable consumption, and production

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Introduction

The Global Plastics Treaty has set the ball rolling for the possibility of globally negotiated actions to end plastics pollution and related health impacts in the next two decades [1], which includes the promotion of the Circular Plastic Economy (CPE) system. Global guidance is trying to deliver common characteristics for a systemic change from a linear to circular economy for plastics, but the implementation and performance will depend on the national circumstances, national pathways adopted, and will happen over the years.

In simple terms, the circular economy (CE) refers to a system [2] where the products, using different pathways, re-enter the value system [3], promote a regenerative system, minimize waste, maximize resource efficiency, and foster sustainable development. In the broader context of sustainable development, to address the issue of 'waste', both in the scientific literature [4] and in practice [5], there is a growing consensus that human activities need to move away from a 'linear' to a 'circular' organizational structure consistent with planetary sustainable living [6, 7]. This effort needs to be simultaneously sensitive to social justice, especially in developing and less developed countries [8, 9]. The ISO/DIS 59,004 [10], part of the ISO59000 series, which is a collection of definitions, best practices, and insights for circular transition, describes it as closing the 'loop' through minimization of virgin resources input, wastes, and emissions. Its most well-known components are Reuse, Reduce, and Recycle, or the "3Rs" [11]. In its earlier appearance, in some research, circularity is discussed synonymously with the 3Rs [12–17]. Also, it has been observed as infrequently practiced despite being advocated and driven mainly by non-government actors [6]. More recent reframing of the concept goes beyond the "3Rs" with Reuse, Repair, Refurbish, Remanufacture, Repurpose, Refuse, Reject, Rethink, Reduce, Recycle, and Recover [11]. See Table 8 for the complete list of historical circularity trends.

Over the past decades, many developing economies have been trying to act domestically on various parts of a circular economy through plastic waste management (PWM), and implement the circularity concept [18–21]. The needs and gaps in PWM exacerbated during the COVID-19 pandemic because of increased plastic consumption and discharge from medical items such as personal protective equipment (PPEs) i.e., masks and gloves, as well as Single Use Plastics (SUPs) items i.e., food packaging, due to reliance on delivery services [22–25].

The need for systemic change from linear to circular practices is well accepted in the literature and policy documents due to the large potential of it to make the development process sustainable with fewer resources [26, 27] through job creation [28] due to progress in technological innovations [29] and availability of substitutes [30]. However, innovation system literature shows that potential benefits do not automatically drive systemic shift [31, 32] unless it is managed consciously [33, 34]. The CPE can be seen as an innovation system to stimulate sustainability by replacing the linear plastic economy (LPE). A combination of structural and functional analysis [35] help in understanding both varying rates of systemic shift [36] and processes or functions that are important for a well-performing system [34, 37]. Smits and Kuhlmann [38] argued in favor of focusing on system-level changes rather than on specific parts.

At this stage, when national scale momentum in developing countries is building up, tracking country-level progress in system structure represented by actors, infrastructure, and institutions, and the state of the system functions can help leverage actions towards

the CPE. Also, provide policy insights and fill an important knowledge gap, going beyond analysis and focusing on parts/components. This paper selects three countries from Asia: India, Indonesia, and Thailand with the objective of providing insights for strengthening the transition of the system from LPE to CPE. The choice of the countries is because of their large share in global plastics trade (Fig. 2; Table 1), high share in plastics pollution in the region, and their national readiness towards circularity [39, 40]. The Plastic Overshoot Day 2024 report's total yearly plastic waste generation per country ranked India as 3rd (9,824,020 Mt), Indonesia as 9th (3,829,170 Mt), and Thailand as 14th (2,910,978 Mt) [41, p. 17]. In the three countries, structural and intersectional inequities are related to gender (disproportionately impacting women), age (children), and caste (disproportionately impacting lower/marginalized castes), and are strongly connected to the informal waste management sector [42–48–49]. Using a multidimensional transition framework, this paper focuses on mapping comparative progress in the CPE system through structure and function tracking. We identify barriers and enablers to make policy recommendations for further development of CPE in these three countries.

This paper is structured as follows: Section 2 describes the context to justify the choice of countries and the primary aim of this study. Section 3 provides an overview of the literature along with research gaps. Section 4 presents the method and materials applied in this analytical study. Section 5 presents the state of functioning of the CPE system individually in three different decades for each of the three countries and an inter-country comparison for the state of the CPE for a recent year, and Section 5 covers discussion and conclusions with policy implications, including that for just transition. The section also includes limitations of the study with suggestions for further research.

Context

Over the past seventy years, global plastic production has increased from 2 tonnes to 450 million tonnes and is projected to increase rapidly [50, Para. 1]. The latest revision of the UN's [51] Sustainable Development Goals (SDGs) indicators mention plastic in Indicator 14.1.1. Transition from the currently practiced LPE [6, 11, 52] to the CPE as shown in the conceptual Fig. 1, with some selected examples to demonstrate that within the circular plastic economy for sustainability, more new products and services will emerge in

Table 1 Plastic waste trade in 2023

Exports to *(MT)* → / **Exports from *(MT)*** ↓	**India**	**Indonesia**	**Thailand**	**Imports from *(MT)*** → / **Imports to *(MT)*** ↓	**India**	**Indonesia**	**Thailand**
India	-	24*	49.5*	India	-	41.9*	11*
Indonesia	429.5	-	155.8	Indonesia	0.007	-	46
Thailand	269.6	46	-	Thailand	48.6	681.4	-

* data for 2019. Source: Created by authors using data from [67]

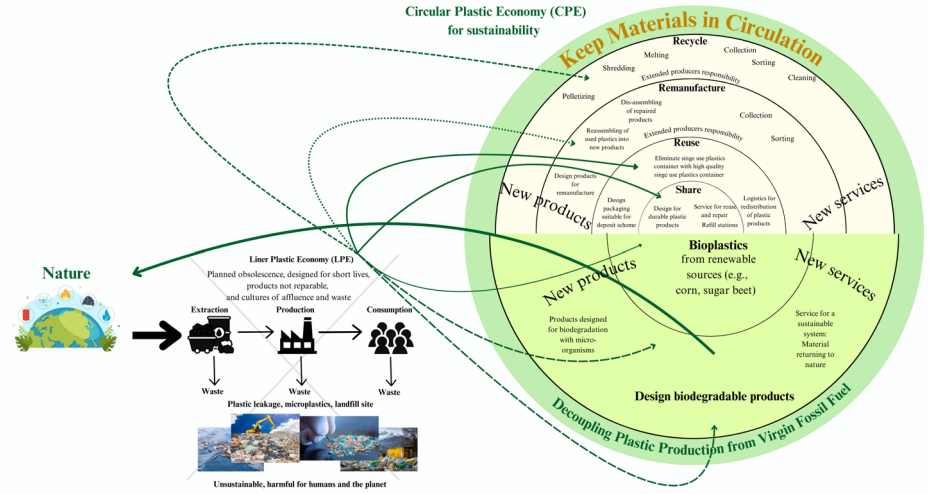


Fig. 1 Conceptual diagram of LPE to CPE transition. The CPE has more potential for creating new economic activities and services in the production and consumption system that are sustainable

the production-consumption system. However, it requires targeted strategies for managing the transition with context sensitive considerations [20, 53] to take advantage of multiple possibilities.

At the national and local scale, the detrimental effects of post-consumer plastic waste leaking into the water bodies, rivers [54, 55], oceans [56], and land, while engineered infrastructures like drainages or dams are degrading biodiversity, food security, and contributing to the severity of extreme events like floods and waterlogging [18, 20, 57]. As remedial measures, there is the extreme approach of (SUPs) usage ban adopted in one form or another in almost all of the countries [58–62]. However, there is also the recognition that production and use continue due to plastic products' versatility, availability, accessibility, low cost, light weight, ease of production, and sterility make it ubiquitous in the packaging and distribution of food and water, as well as application in electronics, agriculture, and infrastructure [63–65] and that legacy plastic material will persist in human society for centuries. So, side by side with bans, various management strategies [5, 66] are also evolving in every country.

Global trade loops in plastics waste with reference to Asia have changed over the years. Historically, in Asia, China was the major importer of plastic waste from developed economies and ranked 1st between 2010 and 2017, but with changes in China's domestic policy in 2018, the position dropped to the thirtieth place and in 2019 to the eightieth place [67]. China has made these efforts since 2013, first, with "Operation Green Fence", a temporary waste import restriction including plastic waste, and then its stricter successor "Operation National Sword" in 2017 [68–70]. These in turn impacted the waste export flow from developed countries to the rest of the world, especially with Southeast Asia (SEA). SEA countries became important destinations for plastic waste from the developed countries [71, 72]. Figure 2 shows some of these changes in a flowchart on the debut of important international laws, actions, and policies related to waste trades or circularity from the period of 2008–2024.

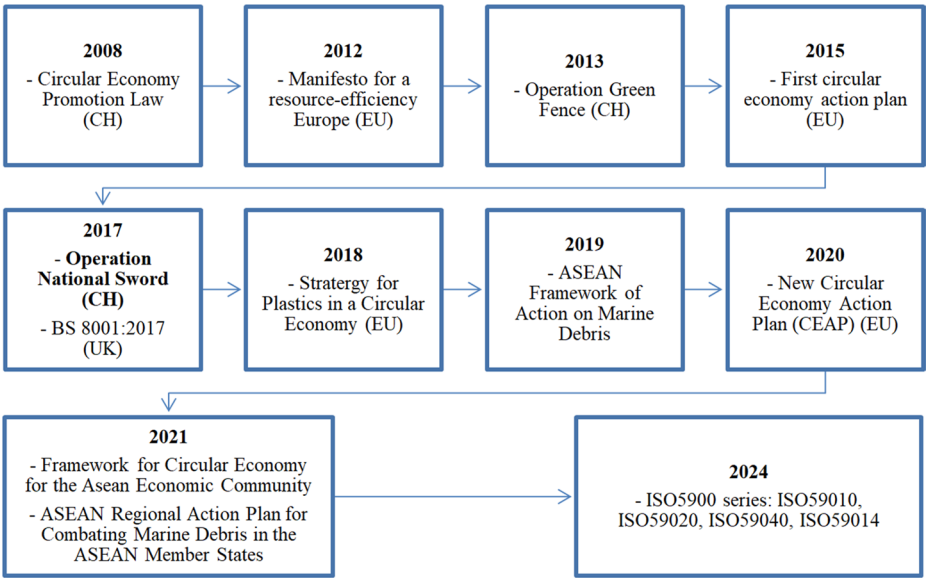
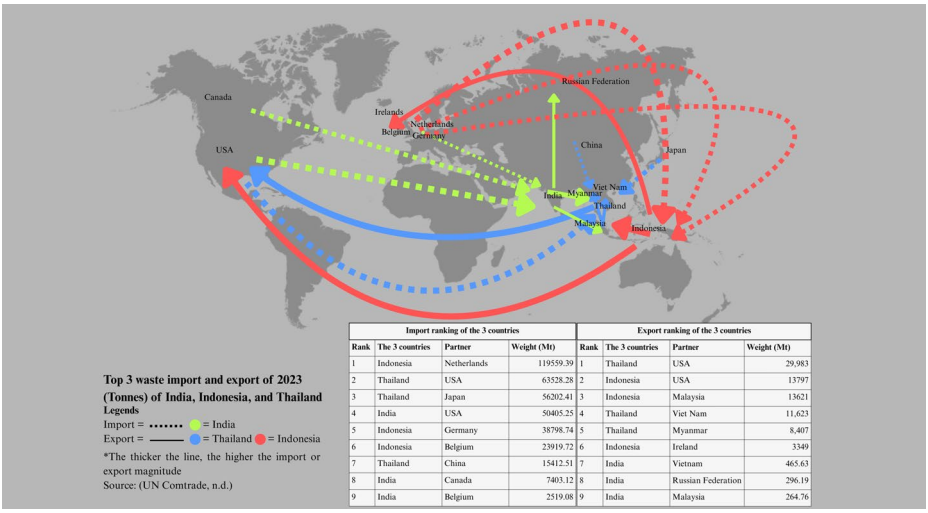


Fig. 2 Circularity law, actions, and policies during 2008–2024 across regions

The United Nations Commodity Trade (UN Comtrade) Database assigns the code 3915 for waste, parings, and scrap of plastics. Based on this data, when ranked by net weight, globally in 2023, India ranked sixteenth in imports (with a share of 64,312 Mt forming 1.38% of total global imports) and sixty-first in exports (with 2,022 Mt forming 0.04% of global exports). Indonesia ranked fourth in imports (with 252,473 Mt and 5.41% share of global imports) and twenty-first in exports (with 42,926 Mt and 0.93% of global exports). Thailand ranked 8th with 201,715 Mt of imports (4.32% of global imports), and in 2022, it ranked seventeenth in exports with 69,145 Mt (1.50% of global exports) [67]. The following Fig. 3 shows the three countries' top export destinations and import sources.

The trade data reveal that developed economies are among the top-ranking waste plastic exporters to the developing economies [41, 67, 71–74]. In 2023, Germany ranked first in exports with 688067.48Mt (14.93% of global), Japan second with 606374.07Mt (13.16% of global), and the Netherlands third with 576702.05Mt (12.51% of global), respectively [67]. There is a pattern with the Netherlands, Japan, Germany, and the USA frequently being the top exporters from 2010 to 2023. When ranked by waste generation per capita, Belgium (148 kg per capita per year), the UAE (127 kg per capita per year), and Oman (126 kg per capita per year) ranked first, second, and third, respectively [41, p. 17]. Amongst the three study countries, Thailand is the highest ranked (45 kg per capita per year), followed by Indonesia (15 kg per capita per year), then India (8 kg per capita per year) [41, pp. 138, 173, 175]. This movement of plastic waste from developed economies to developing economies started around the late 1990s because of cheaper labor, lax environmental regulation, and ease of repurposing recycling materials [75]. Compared to the flow with the developed countries, intraregional plastic waste trades amongst the three study countries are very small (Table 1).



Import ranking of the 3 countries				Export ranking of the 3 countries			
Rank	The 3 countries	Partner	Weight (Mt)	Rank	The 3 countries	Partner	Weight (Mt)
1	Indonesia	Netherlands	119559.39	1	Thailand	USA	29,983
2	Thailand	USA	63528.28	2	Indonesia	USA	13797
3	Thailand	Japan	56202.41	3	Indonesia	Malaysia	13621
4	India	USA	50405.25	4	Thailand	Viet Nam	11,623
5	Indonesia	Germany	38798.74	5	Thailand	Myanmar	8,407
6	Indonesia	Belgium	23919.72	6	Indonesia	Ireland	3349
7	Thailand	China	15412.51	7	India	Vietnam	465.63
8	India	Canada	7403.12	8	India	Russian Federation	296.19
9	India	Belgium	2519.08	9	India	Malaysia	264.76

Fig. 3 Top three plastic waste import sources and export destinations for India, Indonesia, and Thailand in 2023. Data from [67]

The conjecture of whether the plastic waste trade movement from developed to developing countries is driven by factors, and creating a situation similar to the well-established debate around pollution heaven [76–79] is not the focus of this paper. Rather, the data here provides context on whether it has given rise to a push for managing circularity at a global scale, which requires both global and national management architectures and actions to align within the Global Plastic Treaty [1].

In this paper, we start by accepting that, in principle, the concept of circularity as a desirable option within national boundaries is well recognized by each of the countries: India, Indonesia, and Thailand, to minimize and theoretically lead to zero plastic waste leakage. Given this starting point and the backdrop discussed above, the primary aim of this paper is to understand: How are the Asian developing economies making efforts to transition from LPE towards CPE, and what functions of the system need more attention to overcome weaknesses and accelerate progress?

Overview of the Literature

Literature search was for the three countries to understand how progress towards the CPE system in these three countries has been assessed or measured, to understand the gap in knowledge. A country-wise overview is presented in the following subsections. Country-wise literature currently is fragmented, reflecting on various elements and/or functions of the system. In India, technological innovation for recycling was the primary focus, while in Indonesia, it is community scale informal initiatives and the roles of various social actor groups that dominated, followed by policy development. While in Thailand, advances in technology and formal business initiatives were at the forefront.

India

Most of the studies in the Indian context focused on the Indian plastic recycling industry and practices while trying to make statements about partial and not systemic progress towards various components of CE [80–82] including challenges in sourcing raw materials by recycling centers [81]. Studies covered formal and informal recycling sectors [81], recycling technology trends [83], as well as the challenges such as sorting, pre-processing, collection, and uptake of recycled plastic by producers [81]. Recycling is only one possible path and process to move towards a CPE. Studies also focused on other processes for moving towards circularity through re-designing of products, the digitization of waste collection, and alternative technologies [81, 83].

Recycling policies and legal frameworks to move towards a CPE were analyzed by Pilapitiya & Ratnayake [84] with comparisons between Germany and India. They found India's intervention on the consumer's end and integrated plastic waste management policies through the *Swachh Bharat Mission* (SBM) [85] initiatives as positive developments.

Compared to the studies above, which focused on any one of the CE transition components, relatively more comprehensive systemic approaches were found in the Commonwealth Scientific and Industrial Research Organization (CSIRO) [86] report. A report by the Observer Research Foundation (ORF) [87] also touched upon multiple components. These studies attempted to provide policy suggestions based on multistakeholder consultations across the plastic value chains for India's transition to CPE [87, 88]. The CSIRO [88] report suggested the importance of solving data gaps on plastic waste to set targets and indicators, monitoring, multi-stakeholder consultations, capacity building, successful grassroots policy implementations, a uniform extended producer responsibility (EPR) policy, and investment in research and development (R&D) to move towards CE. The ORF [87] report attempted to quantify the social cost of a business-as-usual scenario and the CE framework by considering different indicators such as plastic production, recycling cost per tonnes, greenhouse gas emission, and the cost of plastic [87].

However, none of the reviewed studies provided a comprehensive picture of the progress through a systemic approach to understand the function level progress or obstacles towards CPE and the departure from the LPE in India [89, 90].

Indonesia

In Indonesia, literature mostly focuses on community initiatives and private sector innovations that have increasingly tried to align with CE principles, emphasizing resource efficiency, waste minimization, and systemic sustainability [91]. The country navigated a complex transition process from a LPE to a CE in managing plastic waste and broader environmental issues [92]. As one of the world's largest archipelagic nations, Indonesia officially recognizes the mounting waste management challenges, with plastic pollution and organic waste among others threatening both ecological balance and public health [93].

Strategies such as community empowerment in Yogyakarta, where communities were trained to manage waste independently, showcase promising models for enhancing CE practices [94]. Waste banks such as the *Turikale* Main Waste Bank in the Maros Regency further highlight successful examples where waste management contributed to the local economy and environmental improvement [95]. While Polyethylene Terephthalate (PET)

and Polypropylene (PP)-based beverage packaging recycling has achieved a relatively mature chain in the Greater Jakarta with rates between 74% and 93%, systemic gaps remain at the national level [96, p. 391]. Key policies such as the Presidential Regulation No. 97/2017 on Household Waste Management and No. 83/2018 on Marine Debris Management [92] demonstrate governmental commitment. Nevertheless, challenges such as a lack of integration among businesses, non-government organizations (NGOs), civil society, and limited eco-friendly market development persist [97].

Community-based initiatives like those in Banjarnegara demonstrated the CE's potential, using pyrolysis to convert plastic waste into liquid fuel, thereby offering economic benefits alongside environmental gains (Martini et al., 2023). Similarly, ecovillage programs in West Java have proven effective in integrating plastic waste management into local economies [98]. In the literature, the role of community scale recyclers is seen as crucial within the CPE, where governance structures and policy tried to balance relational and contractual approaches to create more sustainable recycling chains [99]. However, recycling infrastructure remains inadequate, and the absence of national standards for recycled plastics continues to undermine consumer trust [100].

Research on CE in Indonesia predominantly adopts qualitative methodologies, such as case studies, stakeholder interviews, policy analyses, and SWOT models. Quantitative studies remain rare and localized [101, 102]. Critical barriers hindering Indonesia's CE transition include cultural behaviors favoring disposability, weak enforcement of regulations, technological limitations, economic incentives favoring virgin plastic, and fragmented stakeholder coordination [103]. There is research gaps in areas related to functions of the system, such as innovation through eco-design integration, producer responsibility mechanisms, consumer behavioral studies, mid-scale technology adoption, and formalization of informal waste sectors.

Thailand

Most of the literature in the context of Thailand synonymously referred to the CE with the reduce, reuse, and recycle principles and best practices [104–111]. Several case studies centered around end-of-life management of plastic waste rather than on avoiding plastic use. Such efforts include the conversion of plastic waste to alternative energy sources, through studying the potential of plastic from landfills to be converted into Refuse Derived Fuel [112], waste returning schemes [105], PET reverse vending machines in malls [113], testing of a multi-purpose digital platform for circular data sharing, awareness raising, and networking [114]. Some of these experienced mixed results, while others were positively received and demonstrated upscaling potential. Marks et al. [9] identified structural variation and social inequities in the budding circular industry. Their findings reveal bias towards large-scale plastic producers and retailers over waste managers and recyclers, who also have the potential for circularity. Jongsuksomsakul [105] found inequal access to knowledge and waste management infrastructures between urban and rural areas, with the latter missing waste segregation bins.

On the other hand, there were local waste management programs in rural areas, such as local government organizations that educated the public on and installed waste segregation systems that were adapted to the local needs [115], similar effort by corporate entities,

with the addition of upcycling [116, 117]. Also, civil society, like the Mirror Foundation, employed the homeless and the elderly by giving them waste sorting tasks and providing the necessary infrastructure [118], academic research on the gaps of the provincial waste management system, and recommending circular based solutions [119], or an individual turning plastic waste into art [120]. Most of these are end-of-life focused.

In summary, all three countries are driven by various ongoing efforts from innovators, communities, businesses, the government, and NGOs. Over the past years, many researchers have attempted to understand how things can improve in some selected dimensions only, how dominant recycling technologies are emerging, and where the barriers are. However, so far, none of the literature in either of the three countries has adopted any systemic framework with multiple dimensions or functions for analyzing progress in various functions that together enable a systemic shift towards CPE.

Method and Materials: Multi-dimensional Transition Tracking Framework (MDTTF)

To understand the state of the CPE system that contests existing social practice of the LPE, technology, organizations, institutions, and processes, it is crucial to know who among the social actors is/are driving the change with what infrastructure and technology choices within institutional mechanisms, which is important to strategically manage/accelerate the system performance in multiple connected and mutually reinforcing dimensions. The multidimensional transition framework [34, 35, 37, 121–128] using the Technology Innovation System (TIS) approach has been utilized widely in the literature in various innovation and country contexts and sectors, such as renewable energies [129, 130], transportation energies, and mobility service provision [131–133], but to a limited extent in the plastics and wood industries [64, 134], and for understanding CE enabling practices [135, 136]. This framework is adaptable and can be developed to generalizable insights through the analysis of interconnecting changing knowledge and technology, societal actors, institutions, and networks [127, 137].

In any transition process, it appeared that there were many trials and errors and muddling through, but it did not mean progress was not happening [138]. So, it is important to provide a lens for more systemic analysis of the transition process. The TIS in general and the MTIS framework in the developing economies context [131] with seven functions (F1-F7) based on a well-established innovation system literature [34, 35, 37] represent seven major dimensions/system functions (Table 2) and provide the approach for systemic analysis to understand how the existing LPE can be transformed to a CPE, and identify the weaknesses and barriers in the system.

It is necessary to review the transition process over a time period to understand how much ground [131] within a CPE field defined by the structure and functions has been covered, a boundary for the field/achievement. Defining such a boundary condition also helps to understand how to change the course of actions, if needed, in the transition path, say for midcourse correction, and in which direction an acceleration might be necessary among the various functions in the system to push towards the boundary. To track system-level change, it is necessary to define a system boundary for a seven-dimensional system.

Table 2 Multidimensional change tracking through 7 functions

MDTTF broad function categories	Real life manifestation	Examples	Rating using a Likert scale
(F1) Entrepreneurial Activity	New CPE relevant business activities, production processes, and installation of new technologies	A business installing a recycling technology, waste collection system, business model for substitute packaging material	0–5
(F2) Knowledge Development	Research, impact assessment, market studies, pilots, and development of prototypes	New processes for recycling, customizing recycling technology for local context, R&D activity, cloth bags to replace plastic bags, and glass bottles for plastic water bottles	0–5
(F3) Knowledge Diffusion	Knowledge exchange, awareness programs, and organization of networking events among stakeholders	Awareness campaigns on CPE, curriculum development	0–5
(F4) Guidance of Search	Guidelines, policies, regulations, awarding accomplishments, setting goals, and expectations	Governments/associations/CBOs publishing CPE guidelines	0–5
(F5) Market Formation	Price and non-price incentives, consumer empowerment, and standardization	Providing tax exemption or subsidies for CPE initiatives, promotion, or advertising of alternative products	0–5
(F6) Mobilization of Resources	Access to financial and non-financial resources, loans, human resources, and access to technology & infrastructure	Upskilling employees with CPE skills, loans with favorable terms and conditions, and special economic zones	0–5
(F7) Creation of Legitimacy	Official endorsement, advocacy work	Legislations such as a ban on SUPs, the government adopting CPE languages and practices, and lobby groups	0–5

Following this broad theoretical and empirical literature [34, 35, 37, 131], we adopted all the functions and dimensions to be of equal importance, as theoretically each of the elements of the system structure is equally important in delivering systemic change to a CPE. By using a *5-point Likert Scale* (Table 2, column 4), we rated each dimension or function. A dimension or function was rated 0 if it was merely at the starting point of change,

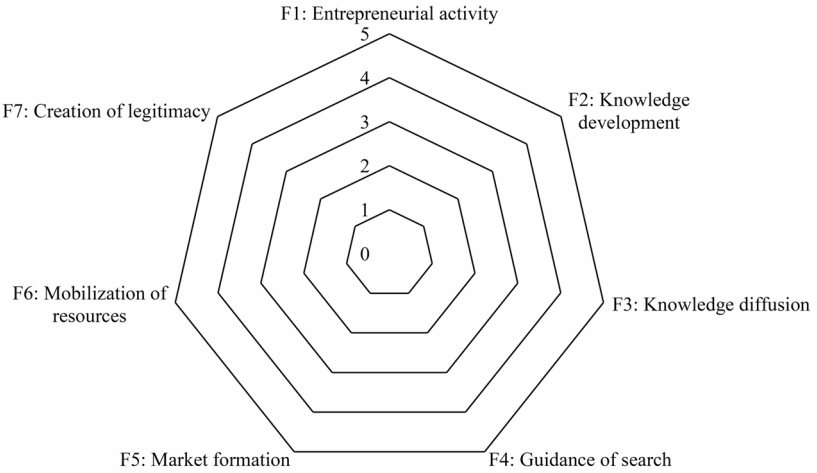


Fig. 4 Heptagon representing the 7 functions for system change towards a CPE

and progress was yet to be made, or we used the maximum of 5 if the desired level of change was achieved. The magnitude of rates greater than zero and less than 5 meant the change was yet to be fully attained. By this rating method (detailed explanations with worked out example is added in Online Resource 1), we drew a heptagon (7-sided polygon) and defined the boundary of the CPE system (Fig. 3).

We defined the center of the heptagon (Fig. 4) by a rating of zero in terms of CPE transformation to represent a fully operational LPE system. When each dimension of the function grows beyond zero and reaches the boundary of the heptagon, then the CPE transformation is achieved, which is a system that can be sustained by its internal dynamics. So, we drew the heptagon with a radius of 7.5 cm, to represent the area to be covered starting from the center. For diagrammatic representation (Fig. 4), the radius of the circle needs to be the same to help compare across time and space.

Application of the MDTTF

To adopt and implement the multidimensional transition framework mentioned in the preceding section, we followed a mixed method where both qualitative and quantitative data were used. The quantifiable multidimensional tracking tool based on qualitative information to monitor the progress of change in the context of the three countries under study was implemented through the following steps:

Mapping CPE Related 'Events' in the MDTTF

The literature search revealed that the three countries were already implementing various actions along various dimensions. We adopted an ex-post analysis based on what actions were already in place and evolving based on the country specific evidence.

We defined CPE related events as the number of actions that were being implemented, and we mapped them across multiple functions. The evidence of such actions was identified from policy documents, civil society reports, news media, journal articles, and so on. In all three countries, there have been targeted efforts to introduce CE related practices, such as the adoption of recycling technologies, business models, and new value chains, and policy interventions. These were constantly evolving to challenge the linear system, augmenting existing technologies, organizational norms, and institutional setups, and thus helped in creating and pushing the boundary of CPE. To apply the MDTTF, we first needed to see how each function was evolving through these events. To know that we needed to map the events to each of the 7 functions, the first step was a mapping exercise of the basic data on such events. We did not consider any expert interviews, as were done in many transition analysis studies. The reason was that expert interview-based results were used as primary data, where the goal was not an ex-post analysis [64]. Some studies used expert interviews [131] to validate the event-based analysis and established that the event-based ex-post analysis through document search yielded similar conclusions as the expert response-based study. So, we took this lesson and decided that for this study, we were conducting an ex-post analysis through event-based analysis. However, data accuracy and reliability are ensured by the sources of information (details of which are in the supplementary material Online Resource 1). To cross-check the scoring-based outcome, we used two approaches: One, an in-person sector expert workshop/conference session including academia, industry, consultants, practitioners, and policy makers. This involves a training workshop on circular plastic economy with rigorously selected participants from Indonesia, Thailand, (and Vietnam). Two, we used the access to experts while presenting our study results to conference session participants (75 participants of which 48 responded) from India. This included testing with a hands-on working session for the first group of participants, and for the second and larger group, we used *Slido*, a multi-platform software for presentation and interaction, to get feedback.

Coding and Scoring

Once the events were mapped in a matrix format for each function, we needed to 'code' the events and then arrive at a quantitative 'score' for each function. For example, with 7 functions and 30 events, there were $7 \times 30 = 210$ cells (Table 3). Table 3 is presented as an illustrative example with only two functions.

Table 3 Illustrative table for coding and scoring

Code/Score	F1	F7
Event 1	Cell 1 (EF1)	Cell 2 (EF3)
Event 30	Cell 3 (EF2)	Cell4 (EF4)
Score (SF_i)	Score SF_1	Score SF_7

Each cell value represented an event's contribution to the evolution of the function. There were two issues we needed to consider for maintaining comparability across functions and across countries. First, as expected, for each function in each country, we got multiple codes associated with multiple events recorded under the function, each code representing each event (Table 3). We could get one 'score' for each function in different ways, but that was not the question or concern for us. The question was how to get one score per function to satisfy the comparability criteria across functions within each country and across countries. We needed to make room for the very likely situation that the total number of events could vary across countries. So, there was a need for implementing a standardization method which could deliver comparability, and we explain the method in the following subsections.

Coding

An event could have several components, which could be mapped to multiple functions. For example, at any point in time, a small recycling business (entrepreneurial activity=F1) engaged in development of a new technology (knowledge development=F2) also conducted a media promotion (knowledge diffusions=F3) from a corporate social responsibility (CSR) fund (resource mobilization=F6). In this example, the event was not linked to or did not play a role to *advance a particular function* (e.g., F7), or *only* partially *advanced a function* (e.g., F1 because here recycling was mentioned without explicitly mentioning CPE), or completely advanced a function (i.e., with explicit mention of CPE which was not the case in the example above).

For the mapping exercise followed by coding, we defined a relation of each event to each of the seven functions through the following coding method (of 0–1):

I. 0 = if an event has no relation or contribution to the function.
II. 0.5 = if an event contributes to a function but partially addresses the element/s of the CPE, or CPE was not the main objective but was an additional benefit/emerged as a co-benefit.
III. 1 = if an event contributes to the function and the CPE transition.

In this coding system, 0 and 1 are straightforward binary numbers representing the absence or presence of some functions. There is no chance of ambiguity or subjective biases. However, here, partial fulfilment of a function represented by 0.5 can give rise to some subjective bias because between 0 and 1, there could have been many numbers representing various degrees of fulfilment. However, in a qualitative assessment through a quantitative scale, there can always be some bias, but the bias is not serious because these numbers provide a degree of relative progress, and the numbers per se do not have a strict meaning except for helping in ranking and comparison. Secondly, two extreme limits are unambiguous. So, this subjective bias in representing partial representation does not impact the interpretation of the functional weakness or strength that we seek to understand.

Scoring and Standardization

As mentioned above, first, we developed scores from the codes, and second, we standardized them to achieve comparability across countries.

Country-Wise Function Scoring As there can be multiple events that strengthen one function, but for the analysis, we need one score per function based on multiple events. To arrive at one score for one function (SF_j in Table 3), we calculated the mean value of the codes per function for each country using equation 1 from the codes of the event-based analysis. We did this for all the three countries (i = 1,2,3).

$$SF_j^i = \frac{\sum_j EF_J}{N_i} \text{ for all i} \tag{1}$$

Where EF = Event code for a function appearing in a cell (as shown in Table 3)

j = Function type 1,2…7.
i = Three countries (India, Indonesia, Thailand).
N_i = Total number of events for each country.

This provided country specific score for each function.

Standardization of Function Scores across Countries After we calculated scores by using equation 1 from above for each country to make them comparable across countries, we standardized the function score SF_j^i by using the common maximum value of 5, which is defined for each function by a *Likert scale* method using the equation of 2

$$\frac{SF_j^i}{N_i} \times 5 \tag{2}$$

Graphical Presentation and Estimating the Area of the Heptagon

This quantification effort through rating, coding, and scoring enabled us to quantitatively estimate the area of the heptagon, which provided us with a quantitative estimate based on qualitative evidence of the maximum value of change towards the full CPE transformation. The area of the heptagon is represented by using the method described in (Butt et al. 2024) by equation (3).

$$Area\ under\ polygon = \frac{1}{2}\left|\sum_i^6 x_i\ y_i + 1 + x_7\ y_1) - \sum_{i=1}^6 (y_i\ x_i + 1 +\ y_7)\ \right| \tag{3}$$

Where (x, y) are the Cartesian coordinates of the vertex of the heptagon

$$x = r \times \cos\theta\ \ and\ y = r \times \sin\theta$$

Where r = radius of the vertex from the polygon's point of origin, and Θ is the angle of the vertex. So, to achieve the full system transformation through the 7-dimensions, we determined that the value of 0 equates to LPE, while attaining the value of 12.72 gets the full transformation to CPE. The country-wise heptagon, once developed by using codes and scores, could also facilitate the estimation of the bounded area, which showed the total area

covered as countries were implementing changes along multiple dimensions, i.e., showing the percentage of change achieved out of the total (100%) required for systemic transformation by each country at any point in the evaluation.

Data

For Step 1 mentioned in the above section and in Fig. 5, we collected events documented for the period 1990–2024 in the three countries as our primary data for the analysis. Data for the study were collected from multiple sources. To identify the sources, we used the Google search engine using the following keywords and phrases in English, Thai, and Bahasa (Table 4).

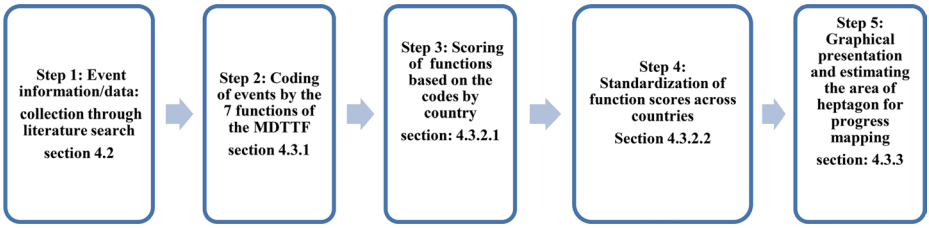


Fig. 5 Flowchart summarizing the methodology

Table 4 Language specific search keywords and phrases used

English	Thai	Bahasa
• Plastic waste management rules • Plastic circular economy India • Business for circular plastic economy • Thailand act/policies/laws on plastics • Thailand circular plastic • Action Plan on Plastic Waste Management • Thailand Bio-Circular-Green Economic • Plastic circular economy • Circularity, progress, Thailand • The Rs of circularity • Plastic waste in South Asia and Southeast Asia • Pollution haven, Thailand • Waste management, inequality • plastic ban effectiveness • Waste pickers, Thailand, Indonesia, India • Circularity equality	• เศรษฐกิจหมุนเวียนพลาสติก (Circular Economy Plastic) • พลาสติกไทยปี1990 (Plastic Thailand 1990) • พ.ร.บ./นโยบาย/กฎหมายเกี่ยวกับพลาสติกของประเทศไทย (Thailand act/policies/laws on plastics) • พลาสติกหมุนเศรษฐกิจหมุนเวียนเวียนประเทศไทย (Thailand circular plastic economy)	• Sampah Plastik (Plastic waste) • Penerapan ekonomi sirkular (Circular economy practices) • Laporan dan Regulasi Sirkulasi Ekonomi (Circular economy report and regulation) • Sampah Plastik di Hulu dan Hilir (Plastic waste through upstream and downstream) • Pemanfaatan Limbah Plastik (Plastic waste utilization) • Bank sampah untuk sirkulasi ekonomi (Waste bank in circular economy)

English translations for Thai and Bahasa are in parentheses

The search fetched many policy documents, government ministerial announcements, publications by international, regional, and local researchers/organizations, websites, news pages, and journal publications. We scanned all the collected literature. Our inclusion criteria for published journal papers, policies, reports, and reports on CSR activities published online were if they include a conscious and explicit reference to the circular plastic economy, or if they addressed at least one function of the MDTTF framework. For the exclusion criteria, it was articles that discuss waste management, but have no focus on plastic waste management, and literature that talks of plastics but has no relevance to waste management and circularity. A final list of 129 selected events (for India, 30 events, for Indonesia, 46 events, and for Thailand, 53 events). Please see Online Resource 1 for the complete list of events from the three countries. Understanding the historical progression of CPE required a retrospective analysis of events. For example, early versions of waste management plans did not include recycling, but future iterations had full circularity integration. So, the absence of the term circularity does not guarantee rejection. We analyzed CPE-related events in the three countries from the first event to the most recent event, i.e., 2024, to map and trace plastic waste- or CPE-related events in each country. All three countries in our study introduced plastic waste-related policy (which, in our terminology, is an event starting in 1990). However, all three countries did not start at the same time. Thailand was the first with plastic recycling activities, followed by Indonesia and India respectively, but all in the same decade of 1990.

Once the events [35, 131] were selected for each country, we mapped them according to the MDTTF functions (see Table 2) for coding, scoring, and graphical presentation, and estimated the area of the heptagon for each country.

Results

In this section, we present the results of the MDTTF as applied to each country and compare the progress towards CPE in the three countries and the subsequent analysis.

Events, Codes, and Scores

We analyzed 30, 46, and 53 events for India, Indonesia, and Thailand, respectively. The method provides comparability of the function values across the countries (Table 5) and within countries over time (for all detailed tables and worked-out examples, please see Online Resources 1). The higher the value, the higher the relative progress. None of the countries are leading in the absolute sense in all the seven dimensions. For instance, India has performed the best among the three in knowledge development, and Thailand the best in guidance of search. Indonesia made the highest progress in knowledge development, followed by guidance of search, but lagging in all seven dimensions when compared to the other countries.

Country-Wise Progress: Heptagon Areas

To understand the progress, we mentioned above that the boundary of the heptagon sets the limit for achieving the transformation to CPE. The smaller the heptagon in size, the less progress achieved.

Table 5 Event-based analysis for India, Indonesia, and Thailand

Functions	India	Indonesia	Thailand
	SFj	SFj	SFj
F1: Entrepreneurial Activity	1.83	0.33	2.03
F2: Knowledge Development	2.67	1.36	2.22
F3: Knowledge Diffusion	0.83	0.82	1.93
F4: Guidance of Search	2.58	1.14	2.78
F5: Market Formation	0.92	0.71	0.94
F6: Mobilization of Resources	1.00	0.16	1.60
F7: Creation of Legitimacy	1.58	0.38	2.78
Total no. of Events (N_i)	30	46	53

The lighter the shades, the lower the achievement level is. The achievement score can be between 0 and 5

Table 6 The area under the heptagon for the three countries

Area of the heptagon (cm sq.)	India	Indonesia	Thailand	Maximum heptagon area
	7.24	1.44	10.80	45.48
% of the area of the heptagon covered	15.92	3.16	23.46	100

The numbers in Table 6 show the area of the three heptagons drawn in Fig. 6 for the three countries. The highest value is from Thailand, followed by India and Indonesia, which shows the relative progress made by each country. This confirms that each country has at least crossed the initial barrier (Fig. 6) and is making progress over time towards CPE. Given that in our case, the total area to be covered for a full CPE transformation was 45.48, the results reveal (Table 6) that only 15.92% progress is made by India over the period of 1998–2024, 3.16% by Indonesia during 1995–2024, and 23.46% by Thailand during 1991–2024. Note that the event analysis revealed that the official actions in all three countries started at different time points. We discuss below how each of the countries approached the issue and took actions that have facilitated their progress so far.

India

In 1998, India introduced its first plastic recycling policy, which was plastic recycling guidelines issued by the Bureau of Indian Standards [139], specifying the manufacture of recycled plastics with its labelling and usage in the market (F1, F2). From 1999 to 2002, policies were introduced to standardize the manufacture, usage, management, and recycling of the plastic materials (F2, F4) [140], but these policies were not mandatory, so they could not influence (F2, F4) much, and no follow-up action was taken on the implementation of these regulations. These policies helped to build awareness and the steps towards knowledge development (F2). India has the earliest event of PWM legal implementation with the *Re-cycled Plastics Manufacture and Usage Rules* in 1999. India's PWM policies

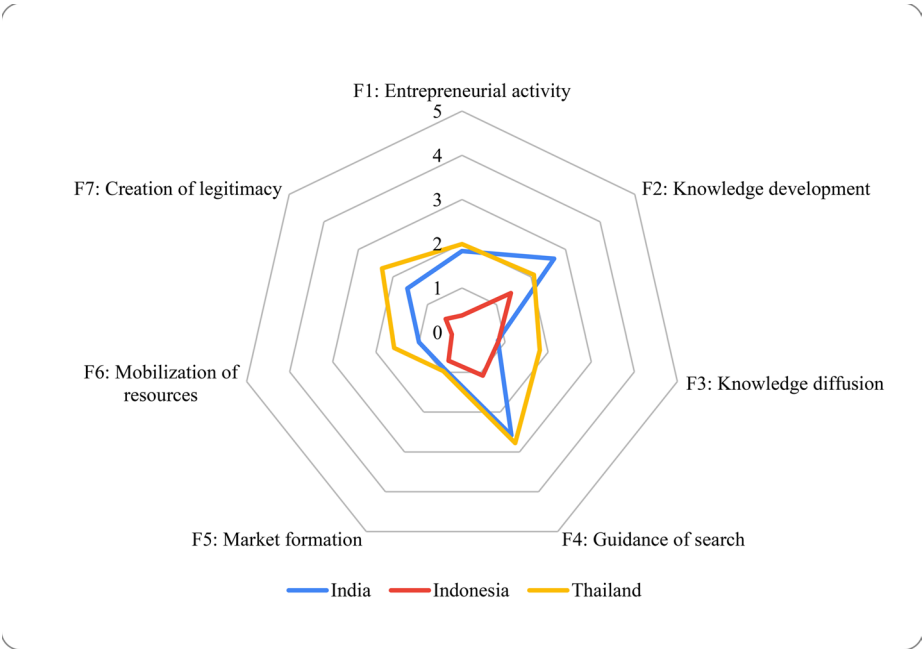


Fig. 6 Overall transition progress for India, Indonesia, and Thailand

are comprehensive and inclusive of various stakeholders by design, with amendments and improvements to existing policies to address issues of PWM (F4). How the state of CPE progressed over time can be seen from Fig. 7 below.

After a decade, in 2011, the Central Pollution Control Board (CPCB) released The Plastic Waste (Management And Handling) Rules, setting roles of the different governing bodies, such as states, municipal corporations, urban-local bodies, to track the plastic manufacturers, recyclers, collectors' management of plastic material, including its release or recovery from the environment [141] (F2, F4). Although the term circularity was not frequently used, CPE elements existed since 2011 through amendments of waste management laws addressing plastic waste issues throughout the value chain (F2, F4, F5). For example, plastic monitoring and reporting, EPR policies, labelling, consumer awareness, recycling, processing of non-recyclable plastics, phasing out SUPs, and environmental fines for violating PWM rules and EPR (F2, F4, F5, F7).

Figure 7; Table 6 demonstrate knowledge development; guidance of search and creation of legitimacy as the strongest functions, primarily due to government policies introduced since the early introduction of PWM rules. The guidelines and policies targeted relevant actors such as manufacturers, distributors, and recyclers, but they fail to channelize and bridge the material flow and cross-communication among the stakeholders. The least developed functions were entrepreneurial activity, knowledge diffusion, mobilization of resources, and market formation through the early adoption stage due to a lack of targeted policies. Post 2018, these three functions gradually picked up the pace, resulting from the plastic industry and recyclers' voluntary action that were integrating CE in their business frameworks through collaborative work to keep up with international plastic industry dynamics [142].

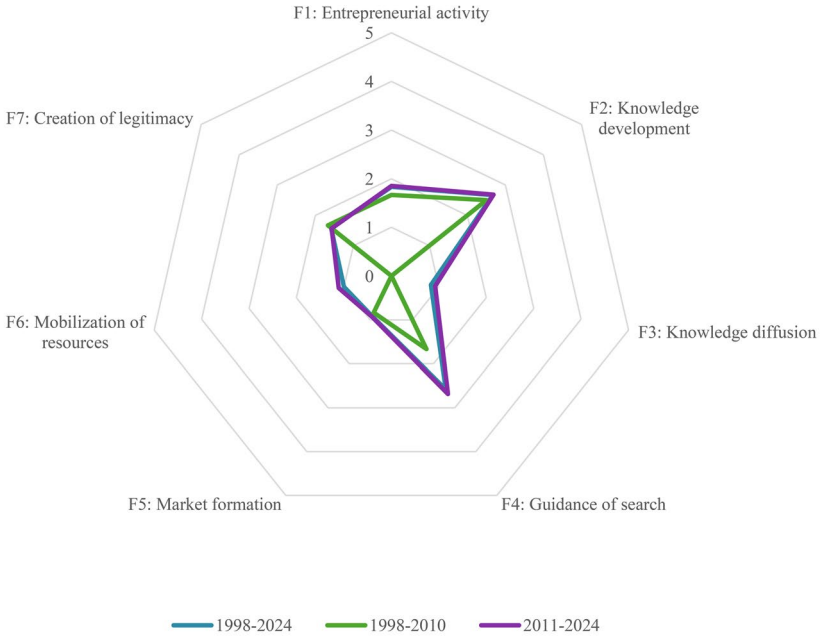


Fig. 7 Decade-wise CPE transition of India spider diagram

Several academic reports mention the need to introduce government policies to provide financial support to manufacturers, distributors, and recyclers to drive CPE products and plastic alternatives for the transition towards CPE. [87, 88]. In terms of policies, India has a strong foundation addressing plastic waste at all levels, but we do not see the practical result on the ground, indicating an implementation gap. These gaps reflect the need for improved waste management infrastructure, awareness, training, and transparency [143].

These formal rules assigned responsibilities and channelized the flow of material in the system, and introduced the concept of EPR. The Ministry of Environment, Forest, and Climate Change (MoEFCC) introduced guidelines and regulations of hazardous plastic waste, focusing on its treatment and import, since the 2008 amendments were made to the Hazardous and Other Wastes (Management and Transboundary) Movement [144], Hazardous and Other Wastes (Management and Transboundary Movement) Amendment, Rules, 2019 [145] (F4, F5). We could see the emergence of efforts to shape the CE, and functions such as knowledge development, knowledge diffusion, guidance of search, and legitimization were getting stronger.

In 2016, plastic waste management and handling rules were modified into the Plastic Waste Management Rules [146] (F4). These rules provided a comprehensive framework for EPR, the addition of different stakeholders, assigning responsibilities, and levying environmental fees or penalties to anyone violating the rules (F2, F4, F7). In 2016, the government also addressed waste management of non-recyclable plastics, providing alternative methods (F2, F4) (Guidelines for Disposal of Thermoset Plastic Waste Including Sheet Moulding

Compound (SMC)/Fiber Reinforced Plastic) [147] and technology with a list of recyclers that manufacturers could contact to ensure their EPR responsibilities.

From 2017 to 2019, the PWM rules were amended with rules, as well as bans and prohibition of import of PET bottle waste, Amendment of Import Policy Condition No.2 of Chap. 39 of ITC (HS) (2017), Schedule-I (Import Policy) [148]. CSR projects also began addressing plastic waste and helping in knowledge diffusion at the community level [149], yet there was no mention of CE per se (F3).

In 2021, the CPE was shaping up, and alternative plastics such as compostable plastics or bioplastics were introduced in the PWM discussion with guidelines on how to identify and dispose [150]. A ban on manufacturing, stocking, distributing, or importing of polystyrene and phasing out of SUPs were some rules amended in the Plastic Waste Management Rule, 2016 [146]. *Swachh Bharat* Mission, a policy, also provided guidelines and funding to set up PWM rules infrastructure with awareness programs at the rural level (e.g., panchayats) (F2, F6) [151].

The Confederation of Indian Industry Initiative, an industry association, was the first to address the CPE through their initiative of the Indian Plastics Pact, started with the Ellen McArthur Foundation [142]. This pact included stakeholders across the plastic value chain and set up realistic targets to achieve a CE (F1, F2, F3, F6).

Post 2022, in the CPE scenario, we found reports and roadmap recommendations by a collaborative academic initiative, which helped the government decide their next step. There were also NGOs working at the community level to diffused and developed knowledge (F2, F3) [86, 87]. Additionally, *NITI Aayog*, an Indian government think tank, formed a CE unit to work towards making a framework and recommendations to stakeholders. The cell was supposed to focus on 10 sectors to implement the CE concept, which also includes plastic waste management (F2, F4) [152]. After 2022, we saw India's CPE scenario entered the early adoption stage, while some of the functions, such as market formation and resource mobilization, were still in the early adoption stage.

Indonesia

Indonesia's transition toward a CPE system development through the seven functions was imbalanced. Despite a relatively high number of events recorded (46), many of these events were concentrated in policy formulation and top-down regulatory efforts, rather than implementation for fostering system-wide innovation (F4). Guidance of search and knowledge development were the most frequent functions, and it reflected Indonesia's reliance on top-down regulations, long-term planning, and technical studies to steer CPE direction. For instance, the issuance of the Government of Indonesia Policy No. 19 (1994) talked about the waste management for hazardous waste [153], showed clear regulatory vision (F4), while a study by the World Bank (2000) provided data-driven insights (F2).

Entrepreneurial activities were emerging modestly, mainly through grassroots or NGO-led projects such as Sungai Watch's upcycling and community collection models. However, the low score in the heptagon suggested that business experimentation remained isolated, lacking national-scale support mechanisms. These micro-level innovations were not backed by strong incentive systems of policy integration, limiting their systemic influence. On the other hand, knowledge diffusion (F3) scored low, with few events explicitly targeting capacity-building or knowledge exchange across sectors. While CSR campaigns, such as

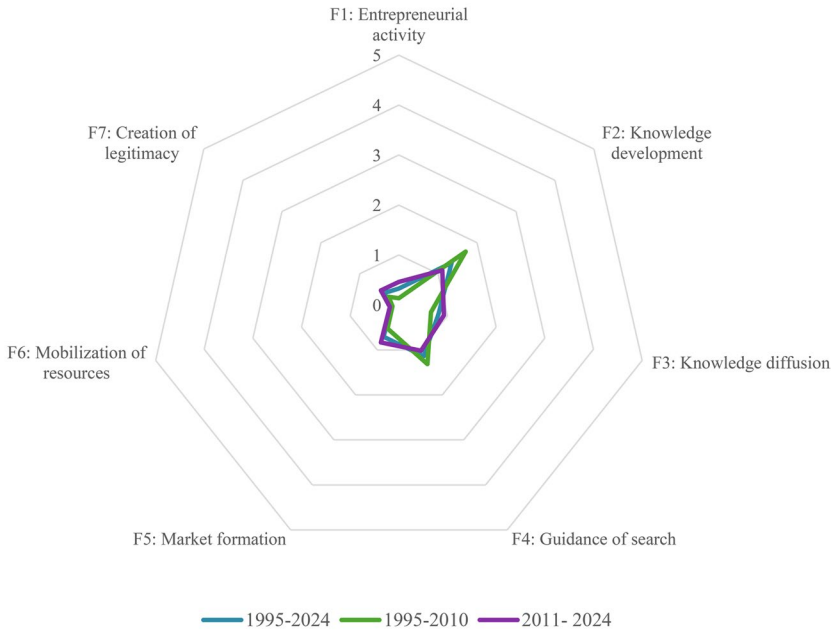


Fig. 8 Decade-wise CPE transition of Indonesia spider diagram

those from Unilever Indonesia during 1994–1999 [154] promoted public awareness, but institutional mechanisms to mainstream learning into industries or local governments were limited. The progress in system transformation and the state of the CPE system are presented in Fig. 8.

Similarly, resource mobilization (F6) scored very low, indicating persistent barriers in funding, infrastructure, and coordination. This was visible in the inconsistent enforcement of Law No. 18/2008 [155] and underdeveloped waste infrastructure, despite supportive legal frameworks. In addition to that, Market Formation (F5) was weakly represented, with events like EPR regulation No. 75/2019 only recently introducing price signals and responsibility mechanisms [156]. Without clear demand-side interventions or recycled content standards, the economic viability of circular practices remained fragile. Finally, creation of legitimacy (F7) showed only moderate activation, mostly through legal codification such as Law No. 32/2009 [157] and international alignment via the Basel Convention [158]. However, informal actors such as small-scale recyclers remain under-recognized, and this reflects legitimacy gaps.

Overall, Indonesia's CE transition showed policy-driven momentum, but lacked balance across the full TIS architecture of functions. It has shown strong efforts in guidance of search (F4) and knowledge development (F2). These functions demonstrate clear vision-setting in a top-down manner. The regulations have not translated into broader systemic activation on the ground, entrepreneurial activity (F1), knowledge diffusion (F3), and resource mobilization (F6) remain critically underdeveloped, particularly through public-private partnership,

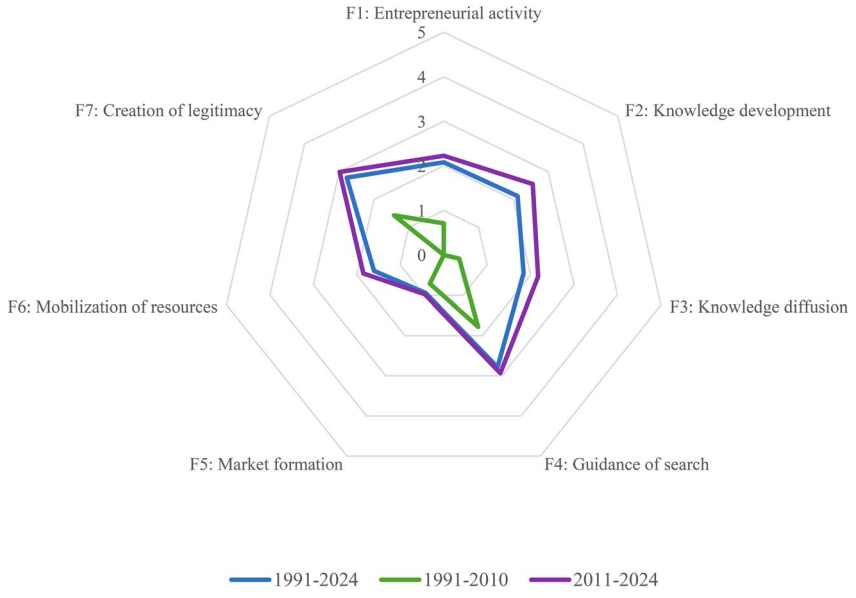


Fig. 9 Decade-wise CPE transition of Thailand spider diagram

resource flows, and institutional legitimacy for non-state actors [159]. Innovation was led mostly by NGOs or donor-supported community projects, lacking institutional mechanisms for scaling or cross-sector integration.

Thailand

In Thailand between 1991 and 2010, PWM activities drove the government's core waste management laws ((Enhancement and Conservation of National Environmental Quality Act, B.E. 2535 (1992), Factory Act, B.E. 2535 (1992), Hazardous Substance Act, B.E. 2535 (1992)), but none mentioned the word recycling. By 1992, the voluntary labelling program for environmental standard certification, the Thai Green Label, was created (F1) [160]. This was the first of a defining trend where Thai entrepreneurial activity drives environmental sustainability and later circularity (F1) [161–163]. In the same year, on the government side, plastic bags were legally classified as waste with the Public Health Act B.E. 2535 (F4). The recycling economy was Thailand's PWM between 1991 and 2022. The performance progress over time in Thailand's CPE system is shown in Fig. 9 below.

Recycling was included in the Ninth National Economic and Social Development Plan with no legal enforcement (2002–2006) (F4, F5). The only enforceable regulation related to recycling at the time was the Ministry of Public Health (MoPH) Notification of 2005, Clause 8 which prohibited the use of recycled plastic for food packaging except for unpeeled fruits (F4, F5) as well as the penalties of fine, imprisonment and revocation of license under the Food Act 1979, Chap. 7 (F4, F5). This displayed limited guidance of search and market formation from the state. Recycling appeared in more subsections of the tenth and eleventh plans (F4), which demonstrated a consistent but limited commitment to recycling-based PWM.

During the years 2011–2017, businesses were taking initiatives to integrate circular elements in their entrepreneurial activities with knowledge development and diffusion, but the term circularity per se was not in use. An example is Indorama Ventures' [164] plan to convert discarded PET bottles to be resin for making drink containers, garment yarns, and colored fibers for automotive and non-woven fabrics (F1). The seafood company Thai Union's SeaChange 2016 and the Ocean Plastic Commitment projects, aimed at creating a circular supply chain (F1) [165, 166]. The petrochemical company PTT Global Chemical's 'Upcycling the Oceans Thailand' program promoted and mobilized resources for plastic waste collection, segregation, and upcycling into designer clothes (F1) [167]. These examples showed Thai corporations spearheading and investing in circularity with their entrepreneurial activities and resource mobilization, a far more concrete progression in circularity than the state side. Nevertheless, the government continued with the 3Rs, in the Twelfth National Economic and Social Development Plan (F4) and the No Plastic Bottle Cap Seal plan by the Pollution Control Department (PCD) to phase out the polluting plastic water bottle cap seal (F4) [168], which continued the pattern of consistent guidance of search and limited market formation but lacking in other functions.

Thailand's Roadmap on Plastic Waste Management 2018–2030 and its guides, plans, and projects mentioned circularity, reinforcing circularity's legitimacy in the public sphere. For example, in 2019, the Ministry of Natural Resource and Environment (MONRE) cooperated with 75 Thai plastic distributors in the Everyday Say No To Plastic Bags and Sevenday Say Goodbye To Plastic Bags projects to reduce or ban plastics at the point of distribution [169] thus strengthening various functions (F1, F4, F6, F7). Successes were achieved from the collaboration of the private and public sector strengths, the state with their guidance of search and creation of legitimacy; and the businesses' entrepreneurial activity and mobilization of resources, as evident with the reduction of 1,300 million plastic bags, plastic water bottle cap sealed phased out, and more plastic reduction plans formulated (F1, F4) [170, Para. 1]. However, circularity was absent from the National Strategy 2018–2037, and legal enforcement was lagging, which again shows the weak guidance of search and mobilization of resources from the state (F4, F5).

The Bio-Circular-Green Economy Action Plan 2021–2027 and the Action Plan on Plastic Waste Management Phase II (2023–2027) introduced the current and defining term for circularity in Thailand, the Bio-Circular-Green (BCG). The BCG framework solidified circularity's legitimacy, being integrated with national sustainability goals, and is Thailand's current approach to circularity (F4, F7). However, despite widespread activities such as circularity trainings and workshops under the BCG framework (F2) [171–173], legal enforcement remained absent, meaning that Thailand's critical gap in circularity remains till now (F5). While private businesses and some community organizations continued with circular activities such as the Seven Clean Seas and Chak Daeng Temple's High Impact Plastic Pollution remOval (HIPPO), a solar-powered waste collection vessel, and the temple conducts plastic bottle segregation and upcycling of said bottles into monk robes [174].

To summarize, Thailand's circularity transition and waste management are under development, systematic and quality data are few (F3, F4), [161] and enforcements are weak [175] i.e., SUPs that were targeted for phasing out were still being sold [176] (F4, F6). Consumer awareness and commitment to circularity are low (F3) [175]. However, there were continuous activities, albeit limited within certain functions, the government, through the BCG framework, diffuses knowledge, provided the guidance of search, legitimacy, facilitate

and funded collaborations between businesses, academia, and civil society on various CPE promotion and research activities as well as some cases of providing infrastructure for PWM (F1, F2, F3, F4) [107, 168, 169, 173]. Businesses had the most on-the-ground CPE activities with their capital, resources, personnel, technology, and infrastructure (F1, F2, F3, F4, F6) [166, 167, 175].

Comparative Analysis

All three countries gradually embraced CPE by moving from a partial approach to a systemic approach towards the circularity concept across the seven dimensions of systemic change over time. However, the state of the CPE system as of 2024 still needs much progress in all three countries. Both Indonesia and Thailand, being members of the Association of Southeast Asian Nations (ASEAN), integrated the ASEAN circular PWM framework into their national CPE plans, reinforcing two functions (F4, F7). Additionally, international organizations such as the United Nations (UN), the Organisation for Economic Co-operation and Development (OECD), the Asian Development Bank (ADB), and the World Bank have been guiding and following up with all three countries to strengthen PWM and CPE in advancing the functions (F2, F3, F4, F7).

Table 7 provides a summary of actions and policies in the national contexts as enablers or obstacles in the CPE system transition. All three countries have low mobilization of resources and market formation through state actions. In Indonesia and Thailand, EPR is voluntary (Thailand has no policies for EPR at all), and development plans often lack quantifiable indicators, thus adversely impacting CPE functions, actionable plans, and budgeting (F4, F5) [9, 175, 177, 178]. For India, there is progress with limited implementation of EPR through the Central Pollution Control Board (CPCB) under the MoEFCC. The CPCB has an EPR portal, which helped the stakeholders in accessing the information of industry stakeholders and, most importantly, the EPR is legally binding with conditions of violation and punishment in the form of fines (F2, F5, F6) [179]. However, the lack of academic knowledge input, more targeted policies, standardized targets, monitoring, malpractices by key stakeholders, and implementation issues are some of the barriers [179].

Creating enabling environments for CPE to be a flourishing economic option relies on government efforts and, in some cases, private sector initiatives to innovate and take first mover advantages in the market to contribute to the progress. Starting in 1999, CSR programs in Indonesia actively launched public awareness campaigns (F1) [154]. In India, CPE as a concept and agenda was pushed by other stakeholders such as academicians, the plastic industry, and CSR projects of the corporate sectors (F1, F2) [87, 88, 180]. By 2018, many CSR projects and entrepreneurial organizations emerged and mostly addressed downstream issues, while others focused on introducing new plastic alternatives (F1, F3) [142, 179, 180]. Thailand had comparatively stronger entrepreneurial and business activities to adopt circularity, and a high frequency of CPE events [174, 181–184]. Businesses created plastic drop-off points [182, 184], built upcycling infrastructure [167, 184], as well as regional plastic circularity projects (F1) [185, 186]. Multinational corporations such as PepsiCo and the Ford Foundation, as market leaders, introduced initiatives and collaborations with civil society and government entities in all three countries (F2, F3, F4) [181, 182, 187, 188]. Although, sometimes such CPE driven business leadership does not get replicated unless there are legally binding rules with implementation support. In Thailand, some retailers do

Table 7 Summary and comparison of the enablers and obstacles of the functions of the three countries

MDTTF functions	Enablers/Obstacles	India	Indonesia	Thailand
(1) Entrepreneurial activity	**Enablers**	++ Uniform standards & indicators with digitization of the certification process + Introducing new technologies for the management of different types of plastics, as well as alternative plastic**s**	+ Community-led enterprise models emerging in local waste systems + Experimental circular waste management gains traction in rural areas	++ Multiple corporate driven circularity projects and CSRs + Circular waste management programs + CPE proficiency + Voluntary circular and green labelling + Existing plastic management infrastructures + SDGs integrated plans
	Obstacles	– Very few upscaling provisions and market expansion - No funding or financing opportunities	- Lack of structural links to national business ecosystems - Projects depend on short-term grants	- - Voluntary and inconsistent application of CPE by businesses - - No EPR laws - Certain CPE initiatives are unprofitable
(2) Knowledge development	**Enablers**	++ Knowledge-based guidelines and policies for plastic waste/recycling management, handling, and mitigation + Public data generation and information platforms	+ Collaboration between the public sector, educational institutions, and NGO is growing + Community-based models foster practical CE knowledge	++ Multiple research projects conducted on experimental CPE designs and methods ++ Collaboration between the public and private sectors in knowledge development + SDGs integrated plans
	Obstacles	- Lack of CE focused technology innovation - Lack of CE focused objective knowledge	- No unified CE research agenda - Institutional learning is fragmented across stakeholders - Limited standardized data infrastructure for CE tracking	- - The public lacks the awareness and consciousness of CPE - Limited public interest in CPE - PWM plans have been scaled back before - CPE development focused only on recycling

Table 7 (continued)

MDTTF functions	Enablers/Obstacles	India	Indonesia	Thailand
(3) Knowledge diffusion	**Enablers**	+ Methods presented and the application of the said methods	+ Workshop supports public awareness in terms of the concept of circularity	+ Public ministries publish CPE plans and guidelines
	Obstacles	– Limited outreach to the public with traditional methods – Lack of financial resources in implementing the methods	- Knowledge stays localized without elevating it to national dissemination - Systemic knowledge transmission mechanisms are underdeveloped	- - Guidelines and plans often lack quantifiable indicators - Limited public reach
(4) Guidance of search	**Enablers**	++ Digitization of data and certifications + uniform standards and indicators at all regional levels	+ National circular economy targets already published and tracked + Local government supports pilots of CPE	++ Circular and Sustainable business practices in branding + The government phased out emissive plastic materials
	Obstacles	– Lack of information on the resource exchange gap in the value chain	- Policy direction lacks clarity and sectoral precision - Weak alignment between policy frameworks and business incentives	- - Lack of laws and policies on CPE and CE
(5) Market formation	**Enablers**	++ Objectives and activities to eliminate non-recyclable materials	+ Informal actors contribute to circular value networks + Functional circular supply chains are emerging in urban centers	+ Markets for recycling by both formal and informal recyclers
	Obstacles	– No financial incentives for CE focused business – No market penetration opportunities – CE is not being the alternative approach among the industry, as it seems an unprofitable strategy	- CE products face weak market demand and pricing signals - Fragmented connection in CE product supply systems	- The government favored supporting CPE initiatives by large corporations - Not many demands for alternative

Table 7 (continued)

MDTTF functions	Enablers/Obstacles	India	Indonesia	Thailand
(6) Mobilization of resources	**Enablers**	+ + CE consultancy firms appearing and policies providing funds to small waste management facilities +Industries working together and mobilizing towards CE	+ Local actors mobilize small-scale funding pools + International partners contribute to early-stage CE funding	+ Business investments in CPE + Government training personnel in CE
	Obstacles	– No provisions of financial incentives for businesses to shift towards CE based - Lack of CE based technology intervention - Lack of network among different stakeholders in the plastic value chain	- No long-term public investment schemes - Access to circular economy finance remains fragmented	- - Multiple issues in waste management systems - - Low or absent budgeting for CPE in the public sector
(7) Creation of legitimacy	**Enablers**	++ Standard permit and certification procedure for different actors ++ A single unit actively working on plastic waste/recycling management	+ Local governments endorse CEP publicly + Community models gain social recognition in circular economy issues	++ The government involved circularity in the primary development plan + CE integrated with the national sustainable framework + CE has cultural legitimacy
	Obstacles	- Lack of implementation and monitoring of guidelines - Lack of infrastructure in place for the industry to follow guidelines	- Informal actors lack legal recognition in circular economy practices - CE legitimacy is geographically and socially uneven	- Limited public reach

Symbols (-/+) represent the presence or absence of the driver of change and ++/-- (more Frequent), +/-(Infrequent)

not distribute plastic bags, but others do (F1, F5, F6) [175]. In Indonesia, many businesses rely on informal waste collectors without offering them legal protection or welfare benefits [189]. A similar scenario is also present in Thailand [190], highlighting the potential risks of raising social inequity in the absence of formalized regulation and enforcement (F1, F4, F5).

In summary, in India, government policies focus on formalizing plastic waste management, banning SUPs, technology, and infrastructure access to tackle different forms of plastic, and EPR policies. Indian businesses face pressure to meet international standards of the circular economy, leading them to form a federation focused on monitoring, research, and development.

For Thailand, the primary contributors are from top-down actors. Government mainstreaming circularity through the Bio-Circular-Green (BCG) economy framework as a national strategy through guidelines. Provides both free and paid training to

stakeholders. The business sector is implementing and/or experimenting with CPE policies, technologies, and infrastructures, along with multiple CSR and funding of civil society initiatives to conduct CPE-related activities. Research on CE and CPE is conducted by academic institutions funded by the Program Management Unit for Competitiveness Enhancement (PMU-C), the National Metal and Materials Technology Center (MTEC), and the National Science and Technology Development Agency (NSTDA). Also, a moderate level of collaboration with civil societies, such as the Chak Daeng Temple. For Indonesia, the primary contributors are from top-down actors with multiple presidential decrees and regulations. There are multiple community-based PWM initiatives, such as training and implementations of recycling, waste banks, and pyrolysis recovery. However, for Indonesia, the enforcement is weak, the recycling infrastructure is inadequate, and there are no national standards for recycled plastic. The gaps come from a lack of integration between businesses, NGOs, and civil society through actor networks, which is suggested as one very important step in a systemic shift in TIS literature [35]. On the business side, the eco-friendly market remains underdeveloped, and virgin plastics use is still financially incentivized.

Discussion and Conclusion

Circular practices in all sectors form a major strategy for sustainability for any country, as they reduce waste in resource use, consumption, and production. Developing countries have embraced circularity as a concept in some form or the other in managing waste, technology development, and policy development since the 1990s. Its application and execution, however, require intensive effort, resources, and time as it is deconstructing an entrenched system of social practice of the linear economy (LE). This study provides a quantitative assessment of the progress made through the multidimensional transition tracking framework defined for a CPE system through structural elements and functions following the Technology Innovation System (TIS) or Modified (MTIS) approaches. Literature on innovation system consider 7 functions equally important for a well-performing system. Weakness in any one function blocks the system's performance. In TIS literature, theoretically, there is no logic for why some functions need higher priority, so we have also taken each function with equal importance for understanding the system dynamics through a structure-function analysis. However, functional analysis at any point in time may reveal weakness in any single function, which might need relative prioritization in the future to bring it on par with other functions' progress, but that is the insight from this analysis.

Among these three countries, Thailand is currently performing the best in overall score, but each country has many good practices to learn from each other, including Thailand, and needs to consider the functions that require deeper focus to accelerate a systemic shift. While for entrepreneurial activity (F1) growth, India's approach to defining standards, the digitization of the certification process is helping; in Indonesia, voluntary community engagement, and in Thailand, voluntary corporate engagement is emerging strongly. But for scaling up, what is needed now is a systemic push by strengthening functions with the requisite external push for financial support, and the introduction of mandatory requirements through the implementation of EPRs. Producers are currently struggling to maintain profitability for sustenance if they follow the EPRs.

Knowledge development (F2) through experimental collaboration and guidance is still at the project level and has not crossed the experimentation stage through a unified research agenda, focused innovation and implementation, a lack of appropriate infrastructure, and a limited focus on recycling. Knowledge diffusion (F3) is happening, but through very limited channels such as academic workshops and government guidelines but with less public engagement and communication, without involving vulnerable groups. Guidance of search (F4) through target setting via top-down process, data management, and branding is getting into the laws, reaching out to the whole value chain, and is weakly aligned with the mainstream businesses in the country. Market formation for the CE (F5) is still very weak.

Across all three countries, the national authorities set up guidelines and principles for encouraging recycling practices and indications for eliminating non-recycled products. However, in the ground-level reality, the market for non-recycled products is equally available from both formal and informal channels, either due to implementation gaps, lack of implementation capacities outside of urban areas, or for the informal sectors, and the formalization of the complex value chain. Financial and human resource mobilization (F6) is very fragmented and inadequate, and without long term targets. Local actors, consultancy firms, and businesses are looking for opportunities, funding sources, and mobilizing funds, but without any long-term commitments to training human resources and starting businesses to have designated CE finance or CE value chain actor networks. For guaranteeing long term sustainability of change, creation of legitimacy (F7) is at a very nascent stage and without any future guarantee in the three countries. While at the policy makers level, support for circular practices appears in development plans, endorsements, standard definitions, certifications, and labels, but lacks any monitoring mechanism, has limited public reach, and no implementation mechanism in place on the economy-wide scale, barring a few experimentations. Policy instruments like financial incentives, capacity building, or social safeguards can make sure that CPE transitions are fair. Achieving circularity in plastics is not only a technical shift but a social one as well. In these countries, the waste (plastics) recycling value chain already relies heavily on informal waste pickers, mostly women, so a just transition must recognize their contribution and integrate them into the circular plastics economy with appropriate rights, protections, and voice [191, 192]. Evidence from accelerated transition projects shows that social and climate injustice can emerge or even be exacerbated when interventions exclude some groups by design or oversight, follow siloed designs, adopt infrastructure- and technology-centered approaches rather than people-centered ones, and lack capacity, financing, and adequate data [193]. Women are often concentrated in the unpaid, lowest-paid, and most hazardous and unhygienic tiers of informal waste work. Thus, the CPE needs to be explicitly gender-responsive using mechanisms such as linking decent-work, (compatible with Sustainable Development Goal 8), standards, and social protection with targeted skills development, access to finance, participation in decision-making, and gender-disaggregated data such that the transition does not reproduce or deepen existing inequities [194]. Similarly, in contexts where caste operates as a durable social hierarchy, waste picking and other forms of waste work are often caste-segregated, with lower/marginalized caste groups disproportionately concentrated in these occupations; this caste–waste nexus reproduces stigma and everyday discrimination that limits access to safer, higher-value roles and to the benefits of formal systems [195]. In other words, when gender, caste, and other forms of socio-cultural hierarchies structure access to work,

space, and services, just-transition measures need to consider explicit anti-discrimination safeguards, representation of marginalized groups in governance processes, upskilling, social protections, and other relevant measures to prevent emergent and ongoing exclusions as new systems formalize, and to achieve circularity targets around collection, sorting quality, and traceability.

The study is a first of its kind in the CPE system structure and functions transition tracking over time (earlier there is a qualitative cross-country study in offshore wind transition in European countries by [35]) to provide a comprehensive analysis of system functions and their relative progress, both qualitative analysis and quantitative assessment based on qualitative data using a multidimensional transition tracking framework in the developing country context. In the ASEAN context, earlier studies focused either on a single country context or on the regional scale to understand the material flow to estimate the circularity rate [196], policy strategy analysis for promoting the CPE [197] for PWM, research publication trends in the region on CE including plastics [198], status on environmental struggles [39], sector specific plastic pollution emissions [199]. However, the current study opens the possibilities of many future research directions to help further develop policy relevant studies to overcome the function-level weaknesses. One can take forward the enablers and barriers analysis as usually applied in the field of studies [200] to understand the hierarchy of the factors to comprehend policy sequences or policy portfolios to systematically address and accelerate the transition process. This itself is a substantial research question that is unaddressed by this research paper. The study has focused on three major countries from Asia at various stages of development and population sizes. While Thailand and Indonesia are categorized as upper-middle-income economies, India is a lower-middle-income economy [201, 202]. All are having plastic wastes generated, traded, and processed on a large scale; however, the full diversity of progress and problems of developing countries cannot be represented by three countries alone, although it can be indicative of the status in these countries. By combining similar approaches with hierarchical barrier analysis for more developed and less developed countries, it can provide a comprehensive Global South perspective. We have only mentioned the scope of persisting social inequity and barriers to just and transformative solutions in CPE being addressed systemically, but a more detailed analysis of intersectional and structural biases, i.e., employment and health related impacts, is needed, especially in relation to historical practices and social marginalization in waste management practices in many regions. The shift in country focus for global trade in waste plastics carries an important message that developing countries are trying to follow the international trends in CPE, but it also shows the need for these countries to create national long-term visions [35, 37] to strengthen their own national legitimacy functions. The current study can be replicated for other developing regions like Africa or Latin America to understand where and how systemic changes are facing blockage at the macro scale to help in making more context-specific recommendations.

Appendices

Table 8 The evolution and trends of circularity

Time period	Traits and trends	Definitions	The different "Rs' of circularity
Pre-1990s The Linear Economy (LE)	- Open ended, Cradle-to-Grave [6] - LE since the Industrial Revolution [6] - Planned obsolescence [203]	- Linear Economy (LE) - Planned obsolescence, consumer goods designed to deteriorate quickly and be replaced, while difficult or impossible to repair, leading to a culture of affluence and waste [203, 204]	None
1990s Inceptions of Circular Economy (CE)	- Closed loop, Biomimicry, Cradle-to-Cradle, Dematerialization - CE does not exist or is in its infancy [205]	- Biomimicry, learn and imitate sustainable practices from nature [206]	
2000–2015 The majority of CE = "3Rs"	- The concept of circularity is equated to or focused on the 3Rs [12-17, [207] or associated exclusively with one of its aspects, i.e., plastic banning [208] - There are exceptions where circularity has more elements than 3Rs before 2015 [6, 205, 207, 209] - Cases of circularity applied with plastic [14–16, 208, 209] - To design waste out of the loop [210] - Four key traits: minimization of material input, keeping materials in the loop as long as possible, reusing materials multiple times throughout the value chain before it is returned safely to the environment, and the preservation of virgin materials. [210]	- A restorative or regenerative industrial system, powered by renewable energy, created to replace the LE. Its goal is to remove waste. It has distinct consumable and durable components of products. [210] - The circular systems should span the entire product life cycle and value chain [211]	- The popular "3Rs": **Reduce**, **Reuse**, **Recycle** [11]
2015–2024 Beyond the 3Rs	- Widespread recognition that circularity goes beyond the 3Rs, usage of the standard "3Rs" to "10Rs" with in-betweens [11, 212] - Circularity "loops" can be shorter or longer [212] - There are still projects where recycling is focused or associated with circularity [213, 214]. Although in some cases where it is visibly about 3Rs, there was a nuanced application of the other "Rs" [212]	- Shorter circular loops - repurpose, redesign, refurbish. Products with maximum value retention across repeated cycles [212]	− 10Rs+: Reuse, Repair, Refurbish, Remanufacture, Repurpose, Refuse, Reject, Rethink, Reduce, Recycle, and Recover [11] - R9s for value retention options: Rethink, Reuse, Repair, Recycle, Recovery, Residual (disposal), Refuse [214, p. 13] - Refuse, Reduce, Resell and Reuse; Repair, Refurbish, Remanufacture, Re-purpose, recycle materials, Recover energy, Re-mine [214, p. 256]

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Declarations

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