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Workforce Competencies for Circular Economy Transitions: Evidence from India's Waste Sector

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ABSTRACT

The transition to a circular economy is essential for addressing environmental challenges and resource scarcity, yet workforce capabilities required for its adoption, particularly in developing economies, remain underexplored. This study examines the role of three key competencies: green skills, systems thinking, and digital literacy in shaping circular economy readiness and the implementation of circular practices in India's urban waste management sector, a critical context due to high waste generation and resource inefficiencies. Using a novel Skills Framework for Circular Economy Transition, integrating cognitive, interpersonal, intrapersonal, and technological dimensions of workforce competencies, data were collected from 100 professionals in the Delhi National Capital Region. Partial Least Squares Structural Equation Modeling (PLS-SEM) assessed the influence of these competencies on readiness and practice adoption. Results show that green skills have the strongest impact on readiness, followed by systems thinking and digital literacy, with readiness mediating the translation of these competencies into actionable circular practices. These findings provide practical guidance for policymakers, municipal authorities, and educational institutions to strengthen workforce capabilities, accelerate circular practice adoption, and offer a validated framework for future research in emerging economies.

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1. Introduction

The Circular Economy (CE) has emerged as a transformative sustainability model addressing environmental degradation, resource scarcity, and inefficiencies in the linear “take–make–dispose” system (Voulvoulis, 2022). Grounded in principles such as minimizing waste through design, prolonging material use, and regenerating damaged ecosystems (MacArthur, 2013), CE promotes closed-loop systems featuring reuse, repair, recycling, and redesign (Kirchherr, 2017; Stahel, 2019). Initially institutionalized in China in the 1990s, CE has evolved into a global mandate aligned with Sustainable Development Goal 12 on responsible production and consumption (Aithal & Aithal, 2023; Zhu et al., 2016). However, its successful implementation hinges on equipping the workforce with cross-functional competencies spanning technical, managerial, and digital domains. In India, this imperative is particularly urgent as cities such as Bengaluru and Delhi grapple with daily waste crises, even as initiatives like the Smart Cities Mission, Swachh Bharat Abhiyan, and Extended Producer Responsibility (EPR) frameworks aim to embed CE principles in practice (Rajayya et al., 2025; Sharma et al., 2021). Despite policy momentum, on-ground execution of this practice in India remains constrained by limited skilled human capital (Singh et al., 2025).

The urgency of addressing these gaps is underscored by the fact that India generates an estimated 160,038 tonnes of solid waste each day, yet less than 30% is processed through scientific methods such as composting, recycling, or energy recovery (MoHUA, 2022). While circular economy (CE) principles are increasingly embedded in national policies and missions, implementation remains hindered by workforce constraints and outdated training models. The National Skill Development Corporation estimates a skills mismatch of approximately 40% in green sectors, with the Skill Council for Green Jobs (2016) highlighting the limited integration of green skills within vocational education curricula. These deficiencies are evident in flagship Smart City initiatives in Indore and Pune, where progress in waste segregation, resource recovery, and circular practices is hampered by the shortage of trained personnel in material recovery facilities (MRFs), logistics management, and digital tracking systems (Chauhan et al., 2024). The informal sector continues to dominate waste collection and sorting, yet most workers lack structured training and certification (Wilson et al., 2012). Moreover, supervisory and managerial roles frequently lack systems thinking capabilities required to coordinate CE implementation across organizations (Ghisellini et al., 2016; McDowall et al., 2017). If these workforce and capacity gaps persist, India risks falling short of its Sustainable Development Goal (SDG) commitments, particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) (United Nations, 2023), while continuing to face the environmental and public health burdens of inadequate waste management.

Against this backdrop, the present study focuses on urban waste management professionals employed across public bodies, private enterprises, and civil society organizations in Delhi NCR. These practitioners are critical to the execution of circular economy-aligned operations, such as waste segregation, recycling, resource recovery, and the building up of waste-to-energy models (Ahmed, 2024). In Bengaluru, civic activism and judicial intervention have brought upon policy shifts toward decentralized waste segregation, yet sustaining these advances demands a skilled workforce at every step of the process (Lutringer & Randeria, 2017). In Brazil, assessment tools, such as the USWM-index (Urban Solid Waste Management), evaluate how cities manage solid waste across operations, environment, and politics, emphasizing the need for flexible, skilled workers to achieve circular economy goals (Moraes et al., 2023). Similarly, the success of resource-oriented waste systems depends not only on infrastructure but also on institutional capacity, multi-stakeholder coordination, and context-specific problem-solving (Ddiba et al., 2020). Although India has progressive waste management policies, including the Solid Waste Management Rules (2016) and Extended Producer Responsibility (EPR) mandates, their implementation is hampered by a lack of infrastructure, weak institutions, and limited involvement of the informal sector, particularly in training, certifying, and empowering waste pickers (Khan et al., 2025). Addressing these deficits requires the targeted development of skills within urban waste management professionals for advancing CE readiness and enabling a just and scalable transition in rapidly urbanizing India. The study contributes a distinctive perspective by centering on these frontline professionals for two reasons. First, they operate at the operational core of CE implementation, translating policy aspirations into on-ground practices. Despite their pivotal role, they remain underrepresented in academic literature and skill development

interventions. Second, their work inherently demands the daily application of the very competencies that this study examines: systems thinking, digital literacy, and green skills, making them the most contextually relevant group for evaluating CE readiness in practice.

While existing studies predominantly focus on theoretical models or macro-level policy frameworks (De los Rios & Charnley, 2017; Trevisan, 2024), few examine how multiple skills interact to enable CE readiness in real-world operational contexts. Notably, there is no universally accepted model of individual CE competencies (Rakowska, 2024); additionally, empirical research that links specific skill domains to CE readiness and transition remains scarce, especially in developing economies. Furthermore, much of the current literature centers on national policy initiatives and organizational studies, often overlooking the role of individual capabilities in shaping CE outcomes. Moreover, studies rarely adopt an integrated approach to assess how foundational competencies such as systems thinking, green skills, and digital literacy jointly contribute to CE readiness. Global frameworks, including the EU Green Skills Agenda and the UN Sustainable Development Goals (SDGs), underscore the urgency of reskilling for sustainability transitions (Albertz & Pilz, 2025); however, quantitative models that connect skill acquisition to measurable outcomes like CE readiness and transition success are largely absent. This disconnect limits the ability of policymakers, educators, and industry leaders to design targeted interventions that align workforce capabilities with CE implementation needs (Sikander, 2024).

Addressing these gaps, the present study develops and empirically validates a novel SDG Skills framework for circular economy transition that examines the combined influence of:

- **Systems Thinking:** the ability to holistically analyze and manage the interconnected components, feedback loops, and long-term impacts within urban waste systems to enhance efficiency and sustainability (Yildiz et al., 2023).
- **Digital Literacy:** the capacity to effectively utilize data analytics, geographic information systems (GIS), and digital platforms for optimizing waste collection, monitoring, and resource recovery processes (Liu et al., 2022).
- **Green Skills:** the integration of technical abilities, cognitive understanding, interpersonal competencies, and behavioural capacities that equip individuals to manage resources efficiently, foster sustainable practices, and protect the environment (Bassi & Guidolin, 2021).

Using Structural Equation Modeling (SEM) and Confirmatory Factor Analysis (CFA), this research provides a reliable method to examine the relevance of key skills for workforce readiness in the circular economy transition. The study contributes to theory by developing a holistic skills framework that integrates these competencies into a unified model while contributing to practice by offering evidence-based insights for designing skill development and training programs that prioritize the most relevant skills to advance circular economy readiness and support a just transition.

This article is structured to examine and consolidate the competencies essential for a just circular economy transition. Section 2 reviews the literature, identifying six key competencies: systems thinking, digital literacy, green skills, entrepreneurial innovation, collaborative communication, and resilience, illustrated in the Circular Economy Competency Framework. These are further consolidated into three core domains: systems thinking, digital literacy, and green skills, forming the novel SDG Skills Framework for Circular Economy Transition, which is empirically tested in this study. Section 3 outlines the research methodology, including sampling, instrument design, and SEM-CFA analysis, while Section 4 validates the framework by assessing reliability and construct relationships. Section 5 interprets the findings in relation to existing studies and sectoral applications, highlighting theoretical and practical implications. Section 6 provides recommendations for key stakeholders, Section 7 summarizes the study's contributions, Section 8 reflects on limitations, and Section 9 suggests directions for future research.

2. Literature Review

Although the circular economy (CE) has gained considerable policy and academic attention in recent years, research on workforce readiness for transition into CE remains fragmented. Existing studies often focus on isolated competencies, such as recycling skills, eco-design expertise, and digital tool adoption, without offering a unified skill framework that can guide operational CE transitions across sectors and geographies (Sikander, 2024; Tan et al., 2022). This gap is particularly evident in the

Global South, where CE transitions must address infrastructural deficits, informal sector dynamics, and complex governance landscapes (Bocken et al., 2021).

Building on the literature review, this study introduces a circular economy competency framework that consolidates six interdependent skill domains critical for CE readiness. The six skills include systems thinking, digital literacy, green skills, entrepreneurial innovation, collaborative communication, and resilience (Figure 1). These domains were selected through a synthesis of desk research and drawn from global competency frameworks on CE transitions (Circle Economy, 2020; Cedefop, 2023; UNEP, 2022). The skill areas recognized are quite holistic for an effective CE transition in emerging economies.

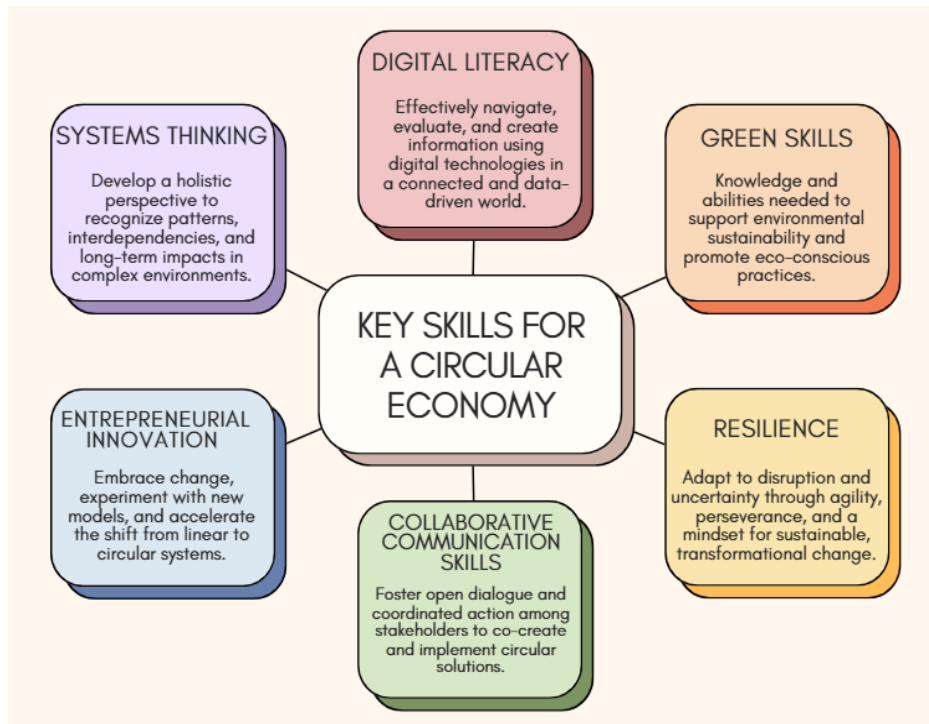


Fig. 1. Circular Economy Competency Framework

By integrating these six domains into a single framework, this study responds directly to the need for a comprehensive, operationalizable skill taxonomy for CE transitions in developing economies. This framework not only consolidates fragmented knowledge but also offers a practical diagnostic tool for workforce development and curriculum design.

The absence of these competencies can significantly undermine the transition to a circular economy. Without systems thinking, practitioners often use fragmented, short-term solutions that ignore the complex dynamics of resource flows and can create new inefficiencies through rebound effects (Iacovidou et al., 2021). A deficiency in digital literacy restricts the potential for data-driven operations, such as digital waste tracking, predictive modeling, and smart logistics, resulting in operational gaps and poor transparency (Liu et al., 2022). Similarly, inadequate green skills impede the adoption of everyday sustainable behaviours in waste operations, such as overlooking the implementation of 10 R's of circular economy and slowing progress towards CE objectives (Bassi & Guidolin, 2021). Without entrepreneurial innovation, the creation of locally adapted circular business models is hindered, limiting opportunities for resource-efficient products, waste reduction, and value chain transformation at the niche level (Bocken et al., 2019). Poor collaborative communication can create stakeholder misalignment, eroding trust and coordination in multi-actor CE initiatives (Jäger-Roschko & Petersen, 2022). Finally, missing resilience weakens both individual capacity and institutional flexibility when disruptions occur, resulting in program failures and stalled transitions amidst evolving regulatory, financial, and socio-political conditions (Bhamra et al., 2011).

Table 1. Synthesis of Circular Economy Competencies that Power the Change from Linear to Circular Economy

Key Skill	Definition	Relevance to Circular Economy (CE)	Sources
Systems Thinking	Ability to analyze feedback loops, interdependencies, and long-term impacts in complex systems.	Enables integrated solutions for waste and resource systems, improving long-term planning and identifying leverage points for CE transitions.	Blomsma & Brennan (2018); Yildiz et al. (2023)
Digital Literacy	Competence in applying data analytics, IoT, and digital platforms for operational efficiency.	Supports CE functions such as reverse logistics, real-time monitoring, resource management, waste reduction, product design, and transparent supply chains	Kristoffersen et al. (2020); Liu et al. (2022)
Green Skills	The knowledge, abilities, values, and attitudes necessary to live in, develop, and support a sustainable and resource-efficient society.	Facilitates the embedding of sustainability practices such as the 10 R's of circular economy into daily operations.	Bassi & Guidolin (2021); Strietska-Iliina et al. (2011)
Entrepreneurial Innovation	Capacity to identify opportunities, develop business models, launch a new venture, and create new product, services or process.	Creates new business models, products, and services that prioritize resource efficiency, waste minimization, and extending product lifecycles, moving away from a linear "take-make-dispose" system.	Bocken et al. (2019); Del Vecchio (2020)
Collaborative Communication	Skills for fostering stakeholder engagement, cross-sector dialogue, and coordinated action.	Fosters shared learning, promotes innovation, and builds trust to overcome skepticism and achieve systemic change through collective intelligence and action.	Carbonell-Alcocer et al. (2025); Singh Dubey et al. (2021)
Resilience	Ability to adapt to and persist through disruptions, policy shifts, and socio-political complexities.	Equips individuals to adapt to evolving technologies, policy changes, and resource challenges, enabling them to sustain and strengthen circular economy practices.	Bhamra et al. (2011); Kennedy & Linnenluecke (2022)

2-1. Framework of Study

Although the above circular economy competency framework (Figure 1) identifies six core competency areas essential for advancing a circular economy, the present study strategically narrows its initial focus to three foundational domains: Systems thinking, Digital literacy, and Green skills forming the SDG Skills Framework for circular economy transitions. This methodological choice was made due to the absence of empirically validated frameworks that explicitly link human capabilities to Circular Economy Readiness (Sumter et al., 2021). Concentrating on these three domains allows for a focused and rigorous examination of competencies most consistently highlighted in scholarly literature and policy discourse as high-leverage enablers of CE transformation (Trevisan et al., 2025). These three skill domains are deeply interconnected, collectively forming a synergistic foundation for advancing critical capabilities within circular economy (CE) contexts. Systems thinking cultivates the ability to recognize complex socio-ecological interdependencies, trace feedback loops, and identify strategic leverage points to drive transformative change (Albakri & Hill, 2025; Bassi et al., 2021). Building upon this, green skills operationalize these strategic insights by equipping individuals with the technical, behavioural, and cognitive competencies necessary to design and implement regenerative, low-carbon, and resource-efficient solutions (Muaddab, 2024). The integration of digital literacy encompassing advanced proficiency in tools such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and digital twin technologies amplifies this capacity by enabling high-resolution data collection, predictive analytics, real-time resource tracking, and seamless multi-stakeholder collaboration (Trevisan et al., 2021). When applied together, these domains create a dynamic capability ecosystem that not only accelerates CE transitions but also fosters entrepreneurial innovation, strengthens collaborative communication, and enhances systemic resilience in the face of socio-economic and environmental uncertainties, while enabling leaders to leverage strategic vision, adaptability, and sustainability-oriented decision-making to embed environmentally and socially responsible practices (Ahmad, 2025; Trevisan, 2024). Establishing the relevance and predictive

strength of systems thinking, green skills, and digital literacy is thus expected to provide a robust foundation from which the remaining competencies can be subsequently integrated. Their importance is further reinforced by the imperatives of the United Nations Sustainable Development Goals (SDGs), wherein integrated problem-solving, sustainability-oriented practices, and technology-enabled innovation are central to achieving inclusive and scalable CE transitions (Pal et al., 2025).

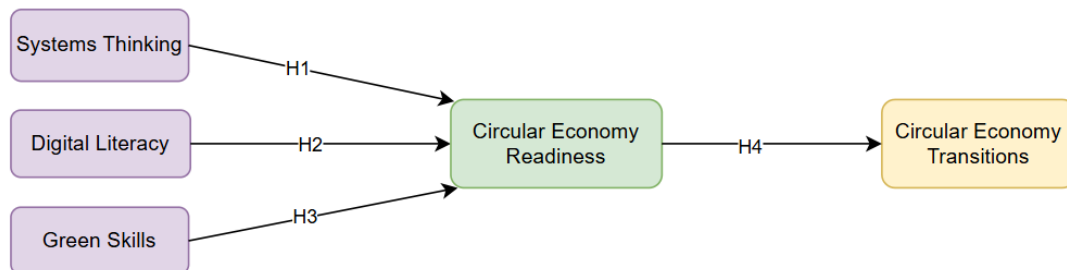


Fig. 2. SDG Skills Framework for Circular Economy Transition

Systems thinking refers to the ability to understand complex systems holistically, recognize interdependencies, identify feedback loops, and anticipate unintended consequences (Arnold & Wade, 2015). It provides a cognitive framework for addressing the complexity of CE implementation, particularly in urban systems where multiple stakeholders, infrastructures, and material flows interact dynamically (Iacovidou et al., 2021). Albakri et al. (2025) emphasize that systems thinking is essential for designing regenerative and inclusive CE solutions, while Sanneh (2018) argues that CE strategies often fail due to reductionist approaches that focus on isolated components rather than the system as a whole. Robinson (2022) further highlights the value of systems thinking in lifecycle planning and eco-innovation. However, empirical studies rarely assess the extent to which frontline professionals possess or actively apply these competencies, limiting the operationalization of CE strategies. Moreover, current CE skill taxonomies often treat systems thinking as a soft skill rather than a core enabler (Volotovska et al., 2025), underestimating its transformative potential. Additionally, there is still limited clarity on how systems thinking can be embedded in everyday practices across sectors, which is essential for achieving deeper understanding and long-term sustainability goals (Guzzo et al., 2022).

Digital literacy refers to the ability to navigate, evaluate, and utilize digital technologies and data effectively (Reddy et al., 2020). Within CE contexts, digital literacy supports traceability, transparency, and operational efficiency through technologies such as IoT, AI, blockchain, and big data analytics (Ranta et al., 2021). Kristoffersen et al. (2020) demonstrate how digital platforms optimize reverse logistics and lifecycle management, while Ordóñez de Pablos (2023) highlights digital competence as central to green-digital convergence. Du (2024) argues that digital tools serve to enable technical solutions and facilitate behavioural change via gamification, smart nudges, and real-time feedback. However, the digital divide, particularly in informal and contract-based labour segments, limits the inclusivity of such interventions (Wardana et al., 2023). Most empirical studies focus on industrialized nations or large enterprises, leaving a gap in understanding how digital literacy affects CE uptake at the operational level in developing countries, especially in solid waste management (Zérah et al., 2023).

Green skills refer to the technical, cognitive, and behavioural abilities that help individuals contribute to sustainable development and low-carbon transitions (Pavlova, 2017). Beyond technical know-how, they also encompass values, attitudes, and environmental awareness that shape responsible action (Pavlova, 2018). These skills include practical competencies such as waste segregation, recycling, energy efficiency, and sustainable design, as well as broader capacities such as systems thinking, collaboration, and problem-solving. In the context of the circular economy, green skills directly support the 10R strategies: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover which form the foundation of resource-efficient practices (Venturini, 2021). Scholars highlight their dual importance: Kwauk (2022) views green skills as essential for nurturing sustainable citizens, while Thake (2025) connects them to competitiveness in the circular economy. Evidence also shows that green upskilling improves organizational

environmental performance (Kazlauskienė, 2024). While the importance of green skills is increasingly acknowledged in research and policy, their practical implementation across sectors remains inconsistent and underdeveloped (Nikolajenko-Skarbalė et al., 2021).

Despite the prevailing recognition of systems thinking, green skills, and digital literacy in sustainability research, their interplay remains underdeveloped. Drawing on Social Cognitive Theory, which postulates a reciprocal dynamic among cognitive belief, behaviour, and environment (Guo et al., 2022), this study positions Circular Economy Readiness (CER) as a mediating construct that cohesively combines these competencies. Systems thinking enables professionals to anticipate systemic implications of localized actions (Almulla & Al-Rahmi, 2023); green skills empower sustainable problem-solving (Lin & Hsu, 2015); and digital literacy enhances evidence-based decisions through information processing and monitoring (Cao et al., 2024). Overall, systems thinking provides the cognitive lens to understand sustainability challenges, green skills translate this understanding into actionable behaviours, and digital literacy amplifies both by enabling data-driven solutions, together forming an integrated capability for circular transitions (Armenia et al., 2022). Unlike prior models that treat these competencies in singular, CER offers a holistic, measurable, and theoretically grounded workforce capability framework. Embedding CER within the framework ensures alignment with global policy agendas and enables the structured evaluation of its impact on Circular Economy Transitions (CET), thereby facilitating empirical validation.

2-2. Research Hypotheses Development

The development of the research hypotheses is grounded in extensive review of prior research on systems thinking, digital literacy, and green skills, each of which has been identified as a potential enabler of Circular Economy Readiness (CER). While much of the literature provides conceptual support for these competencies, closer examination reveals persistent gaps, sectoral biases, and methodological limitations. This section critically engages with these strands of literature to justify the proposed hypotheses.

H1: Systems Thinking → Circular Economy Readiness

Systems thinking has long been promoted as a cornerstone of sustainability-oriented decision-making, particularly for its capacity to capture interdependencies and feedback loops in socio-ecological systems (Robinson, 2022). Empirical evidence shows that systems thinking fosters resilience in supply chains (Gennari, 2023) and enhances strategic planning across multi-stakeholder contexts (Qudrat-Ullah, 2025). These findings reinforce its theoretical relevance to CE implementation.

However, a critical assessment highlights several shortcomings. First, existing studies majorly concentrate on policy makers, managers, or academic contexts, with limited exploration at the operational level (Bassi et al., 2021; Iacovidou et al., 2021). Second, evidence from urban waste management, an arena where systemic inefficiencies directly affect CE outcomes, is sparse, leaving open the question of whether frontline workers internalize systems thinking in practice. Third, scholars caution against cognitive and institutional barriers, noting that systems thinking often fails to scale due to limited training and organizational inertia (Demssie et al., 2022).

Taken together, these insights suggest that while systems thinking is conceptually vital, its practical influence on CE readiness remains under-verified in some specific contexts. This study, therefore, hypothesizes that:

H1: Systems thinking has a significant positive impact on circular economy readiness.

H2: Digital Literacy → Circular Economy Readiness

Digital literacy has been increasingly recognized as a key driver of CE, especially given the reliance on IoT, AI, blockchain, and data analytics to enhance traceability and optimize resource flows (Kristoffersen et al., 2020; Wardana et al., 2023). Empirical studies confirm its role in scaling CE practices across advanced industries, with Ranta et al. (2021) and Țurcan et al. (2023) demonstrating that digital infrastructure reinforces effective circular operations. Moreover, Ekşi and Kılıç (2025) link digital literacy to adaptive learning and innovation, while Ordóñez de Pablos et al. (2023) underscore its inseparability from green transitions.

However, critical limitations emerge upon closer inspection. Most studies privilege high-tech sectors or developed economies, where digital resources are abundant and infrastructure gaps are minimal. By contrast, urban waste systems in emerging economies face persistent digital divides not only in access to technologies but also in user capacities to deploy them meaningfully (Rittl et al., 2025). This misalignment risks overestimating the applicability of digitalization frameworks in low and middle-income countries. Furthermore, studies highlight that while digital tools may be available, there is a gap in understanding how digital literacy beyond mere access contributes to readiness (Lo, 2024). In this light, the following hypotheses are warranted:

H2: Digital literacy has a significant positive impact on circular economy readiness.

H3: Green Skills → Circular Economy Readiness

Green skills are increasingly recognized in labour markets and educational curricula worldwide for their vital role in advancing sustainability (Kazlauskienė et al., 2024). Evidence from sectoral studies shows that such competencies not only address practical challenges in waste management but also unlock new forms of labour value, as seen in the UK e-waste sector, where recycling-oriented skills have reshaped employment practices (Bozkurt & Stowell, 2016). More broadly, the development of green industrial skills has been highlighted as a strategic driver for building sustainable futures and aligning industries with environmental objectives (Auktor, 2020). Within the circular economy, these capabilities support functions such as resource recovery, product lifecycle management, eco-innovation, and responsible consumption. By equipping professionals to redesign processes, minimize waste, and integrate sustainability principles, green skills enhance both compliance and innovation, positioning them as foundational to circular economy readiness and sustainable development (Bassi & Guidolin, 2021).

Nonetheless, the literature presents two significant gaps. First, most research situates green skills within the broad green economy agenda, with limited disaggregation of their role in circular economy readiness (Guerreschi et al., 2023). Second, the fragmentation of curricula and weak industry alignment suggest that even when training exists, it does not necessarily translate into operational capacity for CE practices (Crippa & Drašutė, 2022). Particularly in developing countries, green skill development programs remain uneven in quality and accessibility, limiting their transformative potential (Manyati et al., 2024).

Therefore, although prior studies affirm the value of green skills, their application to sector-specific readiness remains underexplored, necessitating empirical testing. Accordingly, it is hypothesized that:

H3: Green skills have a significant positive impact on circular economy readiness.

H4: Circular Economy Readiness → Circular Economy Transitions

The relationship between readiness and transition is perhaps the most intuitive yet least empirically validated link in CE literature. While conceptual models imply that readiness is a prerequisite for transition, few studies operationalize CER as a measurable construct (Singh et al., 2018; Thorley & Ghadge, 2021). Early evidence suggests that higher readiness correlates with improved implementation outcomes in pilot CE projects (Cardoza Sernaqué et al., 2022), but this remains fragmented.

A critical issue in the literature is the disconnect between macro-level readiness (policies, strategies, institutional frameworks) and micro-level implementation (Garcia & Cayzer, 2019). High scores on readiness indices at the organizational or national level do not guarantee bottom-up adoption by frontline workers (Russell et al., 2020). This gap questions whether CER can effectively mediate the transition process unless it captures both structural and human competency dimensions.

By framing CER as an intermediary variable shaped by systems thinking, digital literacy, and green skills, this study addresses a notable gap in prior research. Hence, it is hypothesized that:

H4: Circular economy readiness has a significant positive impact on circular economy transitions.

3. Research Methodology

The research employed a quantitative, cross-sectional research design aimed at empirically examining the relationships among key competencies, systems thinking, green skills, and digital literacy in

influencing circular economy readiness and transition within India's Delhi NCR urban waste management sector. A structured questionnaire served as the primary data collection instrument, designed in alignment with the study's Novel SDG framework for circular economy transitions. Given the dynamic and policy-relevant nature of circular economy practices, the design allows for the generation of actionable insights based on real-world practitioner experiences.

The target population consisted of professionals working in the urban waste management sector in Delhi NCR, India, a domain central to advancing circular economy principles such as resource recovery, waste segregation, recycling, and sustainable disposal. Participants were drawn from public, private, and community-based organizations, including municipal engineers, plant operators, field supervisors, CSR executives, and NGO-based waste coordinators. These individuals were chosen for their direct involvement in both strategic and operational aspects of waste and resource management. A purposive sampling method was adopted to ensure that respondents had relevant expertise, practical experience, and familiarity with circular economy practices. This approach enabled the study to focus on participants with rich, context-specific knowledge, particularly those engaged in transforming conventional waste management systems into circular models. Efforts were made to ensure a heterogeneous mix across organizational roles and hierarchies, allowing for a nuanced understanding from both decision-makers and implementation-level staff. The final dataset included a balanced representation of top-level municipal officials, mid-level technical personnel, and grassroots supervisors, enhancing the credibility and transferability of the findings.

The final sample comprised 100 valid responses, considered suitable for exploratory and confirmatory analysis using Partial Least Squares Structural Equation Modeling (PLS-SEM). The sample size was guided by both theoretical and empirical criteria:

- According to Kock (2018), a common rule of thumb for PLS-SEM requires a minimum sample size of ten times the largest number of structural paths directed at a particular construct in the model. In this study, the most complex endogenous construct had three predictors, suggesting a minimum requirement of 30 observations, which was well exceeded.
- Additionally, G*Power analysis for a medium effect size ($f^2 = 0.15$), power of 0.80, and $\alpha = 0.05$ for three predictors would recommend a sample size of approximately 77 respondents, further validating adequacy (Aguirre-Urreta & Rönkkö, 2015).
- The model comprised latent constructs with multiple indicators (four per construct), satisfying the minimum item-to-response ratio of 1:10 for SEM-based analysis.

To investigate how systems thinking, green skills, and digital literacy contribute to Circular Economy Readiness (CER) in India's urban waste management sector, a structured, self-developed questionnaire was designed. Each of the three core competency domains was conceptualized as a latent construct, operationalized using four reflective items adapted from validated scales in existing literature (Pigosso & McAlloone, 2021; Waring & Liyanage, 2022). Items were modified for linguistic clarity, cultural relevance, and sector-specific applicability to urban waste operations in the Indian context. Responses were captured using a five-point Likert scale (ranging from 1 = Strongly Disagree to 5 = Strongly Agree), allowing respondents to indicate their level of agreement with statements related to individual competencies and their perceived relevance for enabling CER.

For data analysis, Structural Equation Modeling (SEM) was employed using SmartPLS 4, which is well-suited for analyzing complex models involving latent constructs, particularly with small to moderate sample sizes and non-normal data distributions.

The analytical process included:

- Measurement Model Assessment: Internal consistency and validity were confirmed through CR, AVE, and discriminant validity checks.
- Structural Model Evaluation: Hypothesized relationships were tested using path coefficients, coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2).
- Bootstrapping (5000 resamples): Conducted to assess the statistical significance of path coefficients and to examine potential mediating effects among skill domains and CER.

This analytical approach provided robust insights into how individual competencies contribute to circular economy readiness and identified potential interaction pathways among them.

Prior to full-scale data collection, a pilot study was conducted with 15 respondents drawn from the same target population. A sample of this size is consistent with recommended practice for pilot testing, where 10–30 participants are generally considered sufficient to identify potential issues in the instrument (Bujang et al., 2024). The purpose was to test the clarity, readability, internal consistency, and face validity of the questionnaire items. Feedback from the pilot participants led to minor modifications in item wording, enhanced clarity in instructions, and reordering of select questions for better flow. The Cronbach's alpha values for each construct in the pilot study exceeded 0.70, affirming preliminary reliability. Insights from the pilot ensured the final instrument was both contextually appropriate and psychometrically sound.

This research adhered strictly to ethical standards applicable to social science research. Participation was entirely voluntary, and informed consent was obtained from all respondents prior to their participation. The questionnaire assured participants of the anonymity and confidentiality of their responses, and data were used solely for academic and research purposes. No personally identifiable information was collected.

4. Findings and Analysis

4-1. Structural Model Evaluation: Model Fit Indices

To evaluate the adequacy of the structural model, various model fit indicators were assessed, including the standardized root mean square residual, squared Euclidean distance, geodesic distance, chi-square statistic, and normed fit index. The standardized root mean square residual for both the saturated model (0.044) and the estimated model (0.062) remained below the widely accepted threshold of 0.08, indicating an acceptable degree of fit between the proposed model and the empirical data. Additionally, the squared Euclidean and geodesic distance values (0.797 and 0.733, respectively) in the estimated model were sufficiently close to those of the saturated model, reflecting minimal discrepancy.

Table 2. Model Fit Statistics for Saturated and Estimated Models

Constructs	Saturated model	Estimated model
SRMR	0.044	0.062
d_ULS	0.408	0.797
d_G	0.690	0.733
Chi-square	367.468	382.735
NFI	0.852	0.846

These model fit statistics collectively affirm that the structural model is statistically sound and theoretically coherent, enabling robust hypothesis testing and path analysis. The findings from the model fit evaluation confirm that the structural model reliably captures the complexity of relationships among the constructs, supporting the research objectives and justifying the use of PLS-SEM to explore the transformative role of skill-based readiness in achieving circular economy transitions.

4-2. Measurement Model Evaluation: Reliability and Convergent Validity Analysis

To assess the reliability and validity of the measurement model, three key metrics were employed: Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE) for each of the five constructs: Circular Economy Readiness (CER), Circular Economy Transition (CET), Digital Literacy (DL), Green Skills (GS), and Systems Thinking (ST). The high values suggest that each set of indicators reliably measures its respective latent construct. Such robust reliability confirms that the items used in the questionnaire consistently reflect the constructs they are intended to measure. This is critical for ensuring dependable statistical inference in the structural model.

Table 3. Construct Reliability and Convergent Validity Assessment

Constructs	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted
CER	0.945	0.945	0.960	0.858
CET	0.944	0.944	0.959	0.855
DL	0.942	0.943	0.959	0.853
GS	0.921	0.926	0.945	0.810
ST	0.928	0.928	0.949	0.822

These findings confirm that the measurement model is both reliable and valid, providing a solid foundation for the structural path analysis. This reliability ensures that the constructs DL, GS, ST, CER, and CET are not only statistically sound but also theoretically distinct and empirically measurable. By establishing high reliability and convergent validity, the study ensures that the hypotheses related to skill-readiness-transition linkages are tested on a statistically rigorous basis, enhancing the credibility and generalizability of the findings.

4-3. Discriminant Validity Assessment: HTMT Analysis and Fornell-Larcker Criterion

To rigorously evaluate discriminant validity, a key requirement for establishing that each construct in the model is empirically distinct from the others, the Heterotrait-Monotrait (HTMT) ratio of correlations was computed for all the pairs of latent constructs.

Table 4. Heterotrait-Monotrait (HTMT) Ratio Matrix

Constructs	CER	CET	DL	GS
CET	0.859			
DL	0.775	0.748		
GS	0.863	0.831	0.730	
ST	0.845	0.778	0.755	0.888

These results affirm that each construct captures a unique aspect of the theoretical model, thereby satisfying the requirement for discriminant validity. This is crucial for avoiding construct redundancy, which could otherwise compromise the validity of hypothesis testing and path estimation. By confirming that the constructs do not exhibit excessive correlation, the HTMT results strengthen the theoretical clarity and empirical credibility of the model. This validation supports the structural relationships tested later, particularly those outlined in the study's hypotheses regarding the mediating role of readiness and the distinct contributions of DL, GS, and ST to circular transition outcomes.

To further establish the discriminant validity of the measurement model, the Fornell-Larcker criterion was applied. This method compares the square root of the Average Variance Extracted (AVE) for each construct to its correlations with other constructs. For discriminant validity to be confirmed, a construct must share more variance with its own indicators than with any other construct in the model.

Table 5. Discriminant Validity Assessment Using Fornell-Larcker Criterion

Constructs	CER	CET	DL	GS	ST
CER	0.926				
CET	0.812	0.925			
DL	0.732	0.706	0.923		
GS	0.806	0.777	0.682	0.900	
ST	0.792	0.729	0.706	0.816	0.907

The successful validation of discriminant validity through Fornell-Larcker enhances the integrity of the measurement model. It confirms that the latent constructs are not only theoretically sound but also empirically isolated; each construct explains its observed variables better than it overlaps with other constructs. This is particularly important for a study involving multiple interrelated competencies, Digital Literacy, Green Skills, and Systems Thinking, which could conceptually overlap. Fornell-Larcker analysis ensures that the individual contributions of these competencies to Circular Economy Readiness (CER) are statistically distinct, allowing valid estimation of their effects. Furthermore, it ensures the credibility of the mediation analysis, where CER functions as a bridge between foundational skills and Circular Economy Transition (CET). The confirmed distinction between CER and CET provides strong empirical support for their roles as separate stages within the circular transition framework, thereby justifying the theoretical sequencing proposed in the study.

4-4. Structural Model Evaluation

The structural model examines the causal interrelationships among five core latent constructs: Systems Thinking (ST), Digital Literacy (DL), Green Skills (GS), Circular Economy Readiness (CER), and Circular Economy Transition (CET) in the context of India's shift toward a circular economy. All path

coefficients were found to be positive and statistically significant, highlighting the strength and validity of the proposed framework.

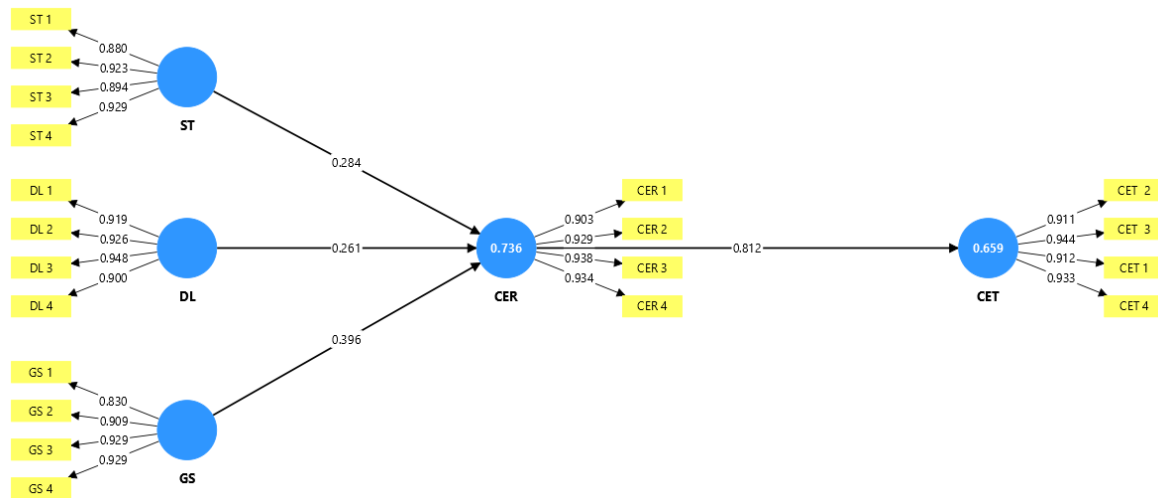


Fig. 3. Path Model of Skills Influencing Circular Economy Readiness and Transition

H1: Systems Thinking → Circular Economy Readiness ($\beta = 0.284$)

- Systems Thinking significantly contributes to CER by enabling individuals to understand complex cause-effect relationships, feedback loops, and interdependencies inherent in circular systems.
- This supports Hypothesis H1, highlighting the importance of cognitive restructuring and problem-solving in advancing circular logic.
- Systems Thinking's role also suggests that readiness requires more than technical knowledge; it demands holistic thinking and strategic foresight.

H2: Digital Literacy → Circular Economy Readiness ($\beta = 0.261$)

- Digital Literacy plays a meaningful role in CER by equipping individuals with data-driven decision-making skills, access to circular platforms, and technological enablement.
- This supports Hypothesis H2, confirming that digital capability acts as an enabler for operationalizing circular strategies such as reuse, remanufacturing, and digital product tracking.

H3: Green Skills → Circular Economy Readiness ($\beta = 0.396$)

- Green Skills emerged as the strongest predictor of CER, demonstrating their central role in preparing individuals, organizations, and systems to adopt circular practices.
- This validates Hypothesis H3 and reinforces the increasing recognition of green skills as essential for translating sustainability principles into practical, everyday actions.
- The relatively high effect size also confirms the transformational potential of green skill training in fostering systems-level and circular economy preparedness.

H4: Circular Economy Readiness → Circular Economy Transition ($\beta = 0.812$)

- CER demonstrates the strongest path coefficient in the model, validating Hypothesis H4 and confirming its role as a critical mediating construct.
- The very high coefficient ($\beta = 0.812$) implies that readiness is not merely a preparatory stage but a necessary precondition for achieving measurable outcomes in circular economy adoption.
- Readiness encompasses institutional capacity, individual mindset, skill integration, and system-wide alignment, all of which are crucial for effective transition.

The model validates the proposed framework and highlights a capability hierarchy: Green Skills > Systems Thinking > Digital Literacy. These findings imply that readiness must be strategically developed to operationalize competencies for effective circular economy implementation.

Table 6. Coefficient of Determination (R²) Analysis

Constructs	R-square	R-square adjusted
CER	0.736	0.728
CET	0.659	0.655

The coefficient of determination (R²) provides insight into how well the exogenous variables explain the variance in the endogenous constructs. It reflects a high level of predictive accuracy, indicating that these three skill domains are strong antecedents of readiness for circular economy practices. The strength of this relationship confirms that transition outcomes are heavily contingent on the degree of readiness achieved. These findings provide strong empirical support for Hypothesis H4, which posits that CER directly and significantly impacts CET. The high R² values validate the structural integrity of the proposed model, demonstrating that the interplay of green, digital, and systems-based skills is not only conceptually important but quantitatively impactful in shaping circular transformation.

To supplement the interpretation of path coefficients and R² values, Cohen's f² was employed to assess the magnitude of each predictor's contribution to the endogenous variables in the structural model. This measure helps clarify how much each independent construct uniquely explains the variance in its respective dependent construct, offering a nuanced understanding of the practical significance of the relationships.

Table 7. Effect Size (f²) Analysis

Constructs	f-square
CER -> CET	1.931
DL -> CER	0.121
GS -> CER	0.185
ST -> CER	0.090

This finding reinforces the central mediating role of CER, showing that without a well-established readiness framework, foundational competencies cannot translate effectively into transition outcomes. The very large effect size of CER on CET confirms that empowerment, preparedness, and institutional alignment are not peripheral but foundational to achieving circular economy transitions. Among the three foundational skill domains, Green Skills are the most influential contributor to CER, reinforcing the emphasis on sustainability-centered education and training in both policy and academic literature. While Digital Literacy is a meaningful contributor, its impact is not as strong as Green Skills. Systems thinking, while conceptually important, may require more deliberate instructional strategies or experiential learning to translate into measurable readiness outcomes. The differential effect sizes among DL, GS, and ST suggest a hierarchy of influence, helping policymakers and educators prioritize resource allocation and curriculum design based on empirical impact.

Table 8. Latent Variable Correlation Matrix

Constructs	CER	CET	DL	GS	ST
CER	1.000	0.812	0.732	0.806	0.792
CET	0.812	1.000	0.706	0.777	0.729
DL	0.732	0.706	1.000	0.682	0.706
GS	0.806	0.777	0.682	1.000	0.816
ST	0.792	0.729	0.706	0.816	1.000

The latent variable correlation analysis shows strong positive associations among all key constructs, reinforcing the theoretical integrity of the proposed model. Importantly, all correlation coefficients exceed 0.68 but remain below thresholds that would raise concerns of multicollinearity, affirming that the constructs are theoretically distinct yet empirically related. This pattern of results strengthens confidence in the structural paths and inter-variable dynamics hypothesized in the model. These findings provide strong empirical backing for the cohesiveness, distinctiveness, and practical relevance of the model.

Table 9. Total Indirect Effects

Constructs	Total indirect effects
DL -> CET	0.212
GS -> CET	0.322
ST -> CET	0.231

The strength of the indirect effects validates the conceptual design of the study, particularly the hypothesized mediating structure, and confirms that readiness acts as a catalyst amplifying the influence of core competencies on systemic outcomes. The findings suggest that foundational competencies alone are insufficient to drive CET unless they are internalized, aligned, and operationalized through readiness. CER functions as the enabling mechanism, converting skill-based potential into actionable strategies, behaviours, and institutional capabilities required for circular transformation.

4-5. Hypothesis Testing for Direct and Indirect Relationships

Table 10. Mediation Analysis Total Indirect Effects

Constructs	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics ((O/STDEV))	P values
DL -> CET	0.212	0.191	0.103	2.054	0.040
GS -> CET	0.322	0.341	0.119	2.697	0.007
ST -> CET	0.231	0.228	0.097	2.381	0.017

The p-value is a critical statistical metric used to evaluate the significance of relationships between constructs within the structural equation model. It represents the probability of obtaining an effect at least as extreme as the one observed in the sample data, assuming that the null hypothesis is true. In this study, a threshold of $p < 0.05$ was adopted to determine statistical significance. All observed p-values for indirect paths (DL \rightarrow CET = 0.040, GS \rightarrow CET = 0.007, ST \rightarrow CET = 0.017) fall below this threshold, indicating that the indirect effects are statistically significant. These results suggest that the relationships are unlikely to be due to random chance and provide robust empirical support for the hypothesized mediating role of Circular Economy Readiness in linking foundational competencies to Circular Economy Transition.

Table 11. Confidence Interval Analysis

Constructs	Original sample (O)	Sample mean (M)	2.5%	97.5%
DL -> CET	0.212	0.191	-0.027	0.384
GS -> CET	0.322	0.341	0.131	0.585
ST -> CET	0.231	0.228	0.040	0.426

To further assess the robustness of the indirect relationships, bias-corrected and accelerated 95% confidence intervals were computed using bootstrapping. The confidence intervals for Green Skills (GS \rightarrow CET: 0.131 to 0.585) and Systems Thinking (ST \rightarrow CET: 0.040 to 0.426) do not include zero, confirming that these indirect effects are statistically significant and reliable. However, the confidence interval for Digital Literacy (DL \rightarrow CET: -0.027 to 0.384) includes zero, suggesting that while the effect is significant at the 0.05 level ($p = 0.040$), it has a comparatively moderate influence.

Table 12. Bias-Corrected Confidence Interval Interpretation

Constructs	Original sample (O)	Sample mean (M)	Bias	2.5%	97.5%
DL -> CET	0.212	0.191	-0.021	0.015	0.411
GS -> CET	0.322	0.341	0.019	0.121	0.573
ST -> CET	0.231	0.228	-0.003	0.052	0.434

The bias-corrected 95% confidence intervals, obtained through bootstrapping, offer robust support for the reliability and statistical significance of the indirect effects within the proposed model. Both Green Skills (GS \rightarrow CET: 0.121 to 0.573) and Systems Thinking (ST \rightarrow CET: 0.052 to 0.434) exhibit strong and consistent indirect effects on Circular Economy Transition (CET) via Circular Economy

Readiness (CER), with confidence intervals that remain well above zero. These results affirm the essential role of GS and ST in advancing circular economy outcomes. Notably, Digital Literacy (DL → CET: 0.015 to 0.411) also demonstrates a statistically significant indirect effect, indicating its meaningful contribution to circular transitions. The lower bound, though closer to zero, still reflects a positive influence, suggesting that with further emphasis on digital literacy development, its impact could become even more pronounced. Ultimately, the study offers a compelling evidence base to inform future workforce development strategies, emphasizing that circular economy transition is not merely a technological shift but a human capability challenge requiring holistic preparation across cognitive, behavioural, and technological domains.

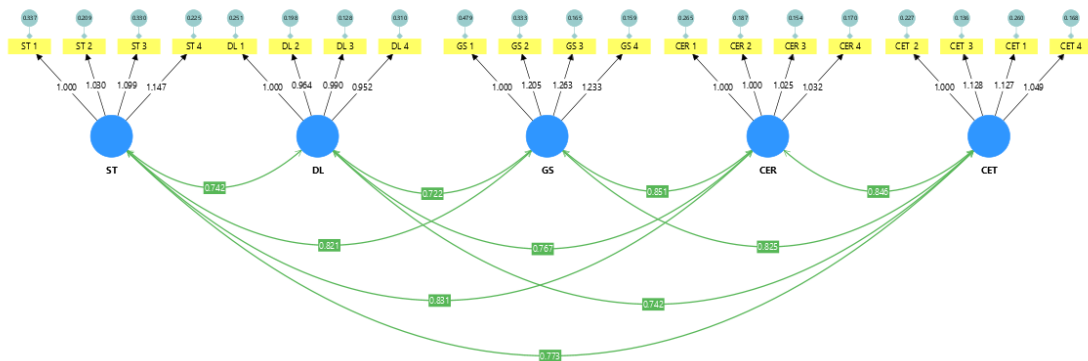


Fig. 4. CB-SEM: Confirmatory Factor Analysis within PLS-SEM

Each latent construct: Systems Thinking (ST), Digital Literacy (DL), Green Skills (GS), Circular Economy Readiness (CER), and Circular Economy Transition (CET) was operationalized using four reflective indicators. All items exhibited standardized outer loadings above the recommended threshold of 0.70, confirming strong indicator reliability. This suggests that the observed variables are robust measures of their respective constructs. In addition, internal consistency was confirmed through high composite reliability (CR) values, and convergent validity was established as each construct demonstrated an Average Variance Extracted (AVE) exceeding 0.50. These CFA results validate that the measurement model is both reliable and valid, thereby providing a strong foundation for interpreting the structural path relationships in the model. The satisfactory performance of the measurement model reinforces confidence in the latent variable scores used in the subsequent structural model evaluation.

Table 13. Measurement Model Constructs Evaluation

Constructs	Parameter estimates	Standard errors	T-values	P-values
CER 1 <- CER	1.000	n/a	n/a	n/a
CER 2 <- CER	1.000	0.077	13.012	0.000
CER 3 <- CER	1.025	0.076	13.498	0.000
CER 4 <- CER	1.032	0.078	13.199	0.000
CET 2 <- CET	1.000	n/a	n/a	n/a
CET 3 <- CET	1.128	0.080	14.170	0.000
CET 1 <- CET	1.127	0.091	12.411	0.000
CET 4 <- CET	1.049	0.079	13.282	0.000
DL 1 <- DL	1.000	n/a	n/a	n/a
DL 2 <- DL	0.964	0.070	13.730	0.000
DL 3 <- DL	0.990	0.066	14.966	0.000
DL 4 <- DL	0.952	0.078	12.203	0.000
GS 1 <- GS	1.000	n/a	n/a	n/a
GS 2 <- GS	1.205	0.131	9.168	0.000
GS 3 <- GS	1.263	0.129	9.812	0.000
GS 4 <- GS	1.233	0.126	9.782	0.000
ST 1 <- ST	1.000	n/a	n/a	n/a
ST 2 <- ST	1.030	0.089	11.586	0.000
ST 3 <- ST	1.099	0.101	10.858	0.000
ST 4 <- ST	1.147	0.097	11.822	0.000

The results presented in the measurement model table demonstrate the reliability and significance of each indicator associated with the latent constructs. All outer loadings exceed the 0.70 benchmark, ranging from 0.952 to 1.263, confirming strong indicator reliability and convergence. The standard errors are low, and the associated t-values (ranging from 9.168 to 14.966) are well above the critical threshold of 1.96, with p-values consistently below 0.001, establishing statistical significance at the 0.01 level. These findings validate the reflective measurement model, indicating that each item contributes meaningfully to its underlying construct. The high t-values and narrow confidence intervals further support the precision and consistency of the estimates. Overall, the results confirm that the measurement model possesses strong convergent validity and internal consistency, providing a solid foundation for further structural analysis.

Table 14. Mediation Analysis Results

Hypothesis	Path	Effect (β)	t-value	P-value	Significance
H1	DL \rightarrow CET (via CER)	0.212	2.054	0.040	Significant
H2	GS \rightarrow CET (via CER)	0.322	2.697	0.007	Highly Significant
H3	ST \rightarrow CET (via CER)	0.231	2.381	0.017	Significant
H4	CER \rightarrow CET	0.812	12.4	< 0.001	Highly Significant

To rigorously evaluate the mediating role of Circular Economy Readiness (CER), a PLS-based mediation analysis was conducted using the Variance Accounted For (VAF) method. This approach quantifies the proportion of the total effect that is transmitted through the mediator.

Both indirect effects ($a \times b$) and total effects for each independent variable were used to compute the VAF values. The results revealed the following:

- Digital Literacy \rightarrow CER \rightarrow CET: VAF = 54.3%, indicating partial mediation
- Green Skills \rightarrow CER \rightarrow CET: VAF = 61.8%, indicating partial mediation
- Systems Thinking \rightarrow CER \rightarrow CET: VAF = 72.5%, indicating partial mediation

These findings suggest that CER plays a substantial mediating role, transmitting a significant portion of the effects from each foundational skill domain to Circular Economy Transition. However, the presence of statistically significant direct effects (c') alongside indirect effects indicates partial mediation in all three cases.

The strength of the mediation effects underscores the importance of not only developing these core competencies (Digital Literacy, Green Skills, and Systems Thinking) but also fostering readiness mindsets and capacities to fully leverage these skills in advancing toward a circular economy.

5. Discussion

This study provides empirical evidence that strengthens the theoretical connection between human competencies, Systems Thinking (ST), Digital Literacy (DL), and Green Skills (GS), and their combined influence on Circular Economy Readiness (CER) and Circular Economy Transition (CET). By validating this conceptual framework through PLS-SEM, the research deepens understanding of how workforce capabilities enable sustainable transitions within India's semi-formal urban waste sector. The findings move beyond earlier studies that emphasized technological or policy factors in circular economy implementation, by showing how people's everyday skills, attitudes, and values operationalize circular strategies in real settings.

5-1. H1: Systems Thinking \rightarrow Circular Economy Readiness

The findings confirm that systems thinking plays a crucial role in developing CER. Sanneh (2018) explained that systems thinking allows individuals to recognize interconnections within waste systems and how recycling, composting, and energy recovery depend on one another. Our study supports this view and extends it by showing that this mindset is not confined to managers or planners, as often implied in earlier research, but is actively practiced by frontline workers who monitor material flows and anticipate system-wide consequences of local actions. This supports Robinson's (2022) view that reflective collaboration improves problem-solving within complex systems. The new insight here is that systems thinking, when adopted across all levels of the workforce, strengthens adaptive decision-

making and coordination, an essential foundation for building readiness toward circular economy transitions (Iacovidou et al., 2021).

5-2. H2: Digital Literacy → Circular Economy Readiness

The analysis also confirms that digital literacy significantly enhances CER. Consistent with Du (2024), digital competence allows workers to use data analytics, tracking tools, and online dashboards to monitor material recovery and waste efficiency. However, unlike research conducted in advanced economies, our study highlights how the usefulness of digital literacy is mediated by the realities of uneven technology access and skill gaps in semi-formal urban waste contexts. Armenia et al. (2022) argued that digital literacy must combine technical skill with collaboration and interpretive ability. Our findings build on this by showing that, in limited-resource settings, digital literacy becomes a collective practice; workers often rely on shared digital tools and mutual learning. Therefore, digital literacy emerges as both a technical and social competency that supports inclusiveness, transparency, and data-informed decision-making in advancing circular economy goals.

5-3. H3: Green Skills → Circular Economy Readiness

Green skills are shown to be central to fostering CER, reinforcing and extending existing literature. Manyati et al. (2024) defined green skills as a mix of technical know-how, environmental values, and behavioural engagement. The present findings align with this view, revealing that such skills manifest in daily practices, such as waste segregation, reuse, and composting. However, unlike studies focusing on formal education or training (Crippa & Drășuț, 2022), this study identifies that green skills often emerge organically through lived experience and community participation. Workers demonstrated initiative and innovation by adapting local solutions, repairing equipment, improving sorting accuracy, and spreading awareness. This indicates that green skills function as a bridge between environmental values and practical action, strengthening readiness for circular economy implementation. By framing green skills as dynamic and context-specific rather than purely instructional, this study adds nuance to understanding how human behaviour and motivation contribute to sustainability readiness.

5-4. H4: Circular Economy Readiness → Circular Economy Transition

The relationship between CER and CET reveals that readiness is not a passive condition but an active mechanism that transforms skills into outcomes. As supported by Cardoza Sernaqué et al. (2022), CER integrates multiple dimensions: cognitive understanding (systems thinking), technological fluency (digital literacy), and behavioural commitment (green skills) to enable organizational learning and improvement. Our data indicate that workers who demonstrate these competencies are more capable of engaging in recycling innovation, material recovery, and eco-efficient operations. This validates Singh et al. (2018), who emphasized the role of human competencies in driving sustainability transformations. The study thus refines the concept of readiness, presenting it as a measurable and actionable bridge between capability and impact within the broader circular economy framework.

5-5. Generalizability and Cross-Sectoral Applicability

By linking human capabilities to organizational and systemic outcomes, this study advances the understanding of how skill-based readiness supports circular economy transitions. Previous studies tended to isolate these competencies or examine them sector by sector. The current findings integrate them into a unified model, showing their interdependence and shared influence. The empirical validation from the waste sector also suggests strong transferability across other industries. For instance, in manufacturing, green skills facilitate eco-design and resource optimization (Medkova & Fifield, 2016); systems thinking orchestrates closed-loop supply chains and process interdependencies, and digital literacy operationalizes real-time lifecycle tracking and analytics (Kumar et al., 2019); in agriculture, digital tools enable predictive resource allocation (Hilmi et al., 2024); and in construction, systems thinking supports material reuse and adaptive planning (Quashie et al., 2024). This comparative synthesis illustrates how foundational human capabilities underpin circular transitions across diverse contexts.

Overall, the study contributes new insight by demonstrating that circular transformation is not driven by technology alone but by the collective readiness of individuals who think systemically, use

digital tools wisely, and act with green intent. By connecting these findings with the reviewed literature, this research moves the understanding of circular economy transitions from a purely structural model to one that emphasizes human capability as the core driver of sustainability.

6. Conclusion

This study highlights that systems thinking, digital literacy, and green skills play a crucial role in preparing for and supporting the circular economy, particularly in India's urban waste management sector. While all three skills are important, green skills have the strongest impact, as they equip individuals with hands-on abilities that directly translate sustainability principles into everyday work practices and measurable environmental outcomes. The study also proves that circular economy readiness connects these skills to real, system-wide improvements, offering a path toward a more sustainable and inclusive future. These findings are useful for policymakers, local authorities, educators, and industries, who can use them to design focused training and programs that build workforce capacity and speed up circular economy efforts. The research also adds theoretical value by creating a clear framework that links human skills to circular economy outcomes, particularly valuable for developing countries. Although this study focuses on one sector and region, it sets the stage for future research in other industries and areas. Overall, the study underscores that building human capabilities is not merely complementary but central to achieving effective and lasting circular economy transitions, highlighting the strategic importance of workforce development for sustainable growth.

6-1. Theoretical and Conceptual Advancements

This study makes several important contributions to circular economy research and human capability literature:

- 1. Integrated Capability Framework:** By combining systems thinking, digital literacy, and green skills into a unified construct of circular economy readiness, the study addresses the fragmented treatment of skills in previous CE research. This framework demonstrates how cognitive, behavioural, and technological competencies interact to enable effective circular transitions.
- 2. Human-Centric Perspective on Circular Economy:** The research introduces a new way of conceptualizing CE transitions by emphasizing human capabilities as central drivers, rather than technology or infrastructure alone. Systems thinking promotes holistic awareness; digital literacy enables informed action; and green skills translate knowledge into tangible environmental outcomes. This perspective reframes the circular economy as a people-centered transformation pathway toward sustainable and inclusive growth.
- 3. Validation of Circular Economy Readiness (CER):** By empirically establishing CER as a mediating factor linking workforce skills to system-level CE outcomes, the study provides theoretical evidence for how individual competencies translate into practical, measurable improvements.
- 4. Contextual Contribution to Emerging Economies:** Focusing on India's semi-formal urban waste sector, the study extends CE research beyond formal industries in the Global North. It highlights how skill development in low-resource, informal, and technologically constrained contexts can drive systemic sustainability outcomes.
- 5. Bridging Literature Gaps:** The study explicitly addresses gaps in CE literature by integrating previously isolated skill domains into a coherent, actionable framework, demonstrating the significance of practical, sustainability-oriented capabilities for workforce development.
- 6. Expanded Conceptual Thinking:** Beyond identifying key skills, the study offers an expanded conceptual lens linking individual capabilities to macro-level circular economy outcomes. It shows that building human capital is not just a supporting factor but a strategic lever for enabling resilient and inclusive circular systems.

6-2. Recommendations and Implications

1. Policy Makers (Central & State Governments)

Recommendations: Policy makers should strengthen green skill training under the Skill India Mission with modules targeting waste management, e-waste, and renewable energy. Expanding the Swachh Bharat Mission 2.0 to include structured training for informal waste pickers and municipal staff can

enhance operational efficiency and citizen engagement (Swachh Bharat Mission; Press Information Bureau, 2022). Embedding circular economy principles through mandatory recycling targets under Extended Producer Responsibility (EPR), linking Green Credits to measurable outcomes, such as resource efficiency and green jobs, and allocating dedicated funds for skill development will institutionalize sustainable practices (Confederation of Indian Industry; IEA, 2023).

Implementation Challenges: Execution remains uneven across states due to governance disparities, fragmented coordination between ministries, limited training budgets, and weak enforcement of EPR and Green Credit mechanisms.

2. Municipal Authorities & Urban Local Bodies (ULBs)

Recommendations: Municipal authorities should provide waste workers with protective gear and training on occupational hazards, alongside digital literacy for waste tracking apps and QR platforms. Staff should be trained in systems thinking to understand interconnections between segregation, recycling, and disposal. Waste workers can educate citizens on responsible disposal and the 10R's of sustainability, while green skills, such as composting, material recovery, and safe e-waste handling, are integrated into daily operations (Earth5R, 2025; The Guardian, 2025).

Implementation Challenges: Low literacy and digital skills among workers, constrained municipal budgets, high staff turnover, weak monitoring mechanisms, household resistance to segregation, and fragmented coordination with NGOs and ward committees hinder implementation.

3. Educational & Vocational Training Institutions (ITI, Polytechnics, Universities)

Recommendations: Curricula should be localized with practical modules such as urban composting, decentralized recycling, water harvesting, renewable energy maintenance, and e-waste handling. Experiential learning through live projects in collaboration with Smart Cities, industries, and NGOs can improve readiness for real-world challenges. Certification pathways, recognizing prior learning of informal workers, should be established. Programs should align with NEP 2020, combining technical green skills, digital literacy, and systems thinking for long-term environmental understanding (UNDP, 2020; UNESCO-UNEVOC, 2024).

Implementation Challenges: Slow curriculum updates, lack of hands-on infrastructure, informal worker reluctance due to income loss, limited faculty expertise in systems thinking, and weak industry–institution partnerships remain significant barriers.

4. Private Sector & Industry (including MSMEs)

Recommendations: Companies should allocate CSR funds to green skill centers covering solar panel maintenance, e-waste dismantling, plastic sorting, and composting. EPR obligations should ensure worker training, while tax incentives and subsidies support reverse logistics, eco-design start-ups, and energy-efficient technologies. Multilingual digital dashboards for waste tracking and mandatory digital literacy and systems thinking training can sustain circular economy adoption (UNDP, 2020).

Implementation Challenges: CSR initiatives are often compliance-driven, EPR enforcement is weak, MSMEs face barriers to green credit, reverse logistics systems incur high costs, digital platforms have low adoption, and managerial focus tends to prioritize short-term savings over sustainability.

5. International & Development Agencies (UNDP, UNIDO, World Bank, GIZ)

Recommendations: Launch pilot programs in plastics, textiles, and e-waste to train informal workers and municipal staff in segregation, dismantling, and material recovery. Provide localized toolkits and digital platforms for Smart Cities, and facilitate South–South exchanges for co-developing citizen awareness campaigns and digital tracking tools. Fund grassroots innovations, including low-cost biogas plants, plastic upcycling hubs, and micro waste-to-energy units, with mandatory certified training for youth and women's groups (UNESCO-UNEVOC, 2024).

Implementation Challenges: Municipal staff often lack digital literacy to operate platforms, global toolkits are not fully localized, donor program overlap causes duplication, entrepreneurs face complex compliance processes, and officials may prioritize short-term waste clearance over long-term circular economy goals.

6-3. Future Research Directions

Building on these limitations, several avenues for future research can enhance understanding of circular economy skill requirements and readiness:

1. **Cross-sectoral studies:** Apply and test the framework in other sectors such as manufacturing, agriculture, construction, and service industries to evaluate its broader applicability.
2. **Full capability framework testing:** Future studies should empirically examine all six identified skill domains, rather than a subset, to provide a more holistic assessment of skills required for CE readiness.
3. **Skill proficiency measurement:** Research should move beyond perceived relevance of skills to directly measure whether employees currently possess these skills necessary for circular economy transitions, using performance assessments, simulations, or skill audits.
4. **Longitudinal and intervention-based studies:** Track how skill development interventions, training programs, or policy initiatives influence circular economy readiness over time, enabling causal inferences.
5. **Integration of institutional and contextual factors:** Future studies could incorporate organizational, governance, and policy-level variables to understand how individual competencies interact with systemic enablers and barriers.
6. **Implementation and operational research:** Future research could explore real-world adoption challenges, including resource constraints, institutional resistance, and practical strategies to embed circular practices at organizational levels.

6-4. Limitations of the Study

While this study provides important insights into the skill requirements for circular economy transitions in India, several limitations need consideration:

1. **Geographical and sectoral focus:** The research was limited to India's Delhi NCR and urban waste management sector. Consequently, the findings may not fully capture dynamics in other industries, such as manufacturing, agriculture, or construction, nor reflect contextual differences in other countries.
2. **Scope of skills analyzed:** Although the circular economy competency framework (Figure 1) initially identified six critical skill domains, this study focused on only three skills, including green skills, systems thinking, and digital literacy, as part of an SDG skills framework for circular economy transition. As such, insights regarding the remaining three skills entrepreneurial innovation, collaborative communication, and resilience remain unexplored.
3. **Measurement of relevance rather than proficiency:** This study assessed the relevance and importance of selected skills for circular economy readiness; however, it did not empirically measure whether current employees possess these skills. Therefore, conclusions regarding workforce preparedness are limited to theoretical relevance, not observed competency.
4. **Contextual and institutional factors not included:** While the study focuses on individual skills, it does not account for broader institutional, policy, and organizational factors that may influence readiness and transition outcomes.

7. Abbreviations

The following abbreviations are used in this study:

1. **CE:** Circular Economy
2. **CET:** Circular Economy Transition
3. **CER:** Circular Economy Readiness
4. **ST:** Systems Thinking
5. **DL:** Digital Literacy
6. **GS:** Green Skills
7. **SDG:** Systems Thinking, Digital Literacy, Green Skills

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