Cleaner and Responsible Consumption 22 (2026) 100468

Contents lists available at ScienceDirect

Cleaner and Responsible Consumption

journal homepage: www.journals.elsevier.com/cleaner-and-responsible-consumption

Understanding circularity knowledge across the general public–expert spectrum: Instrument development and cross-national evidence from six European countries

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ARTICLE INFO

Keywords:
Circularity knowledge
Built environment
Instrument development
Item response theory
Cross-national evidence

ABSTRACT

Circular Economy is increasingly recognized as a multidimensional transition necessary for resource efficiency in the built environment; however, its implementation is hindered by fragmentation. This study investigates the dynamics of circularity knowledge across the public-expert spectrum using a psychometrically validated instrument supported by Item Response Theory. Empirical data were collected from the Netherlands, Belgium, Poland, Türkiye, Romania, and Italy, representing diverse regulatory, educational, and economic settings. The results demonstrate that circularity knowledge is not a binary paradigm but a layered, permeable continuum. While professional participation and advanced higher education are significant determinants of higher circularity literacy, the study reveals a knowledge ladder effect where entry-level higher education provides limited benefits relative to the general public's knowledge levels. The instrument demonstrates robust targeting across the population, evidenced by a strong correlation ($r = 0.812$) between latent proficiency and raw scores, which pinpoints a significant transition threshold at 43.3 points that separates academic preparation from verified expert-level circularity literacy. It shows that although experts are well-calibrated, groups with lower knowledge initially exhibit significantly overconfidence, which only corrects after evaluation-focused reflection. Cross-country analysis confirms structural validity of the tool as a transferable latent construct and demonstrates that specialised curriculum integration leads to knowledge convergence regardless of national origin. It concludes that systemic curriculum integration, practice-based learning, and the use of diagnostic tools to harmonize stakeholder contributions in participatory settings (e.g., Urban Living Labs) are critical levers for accelerating the transition to a circular built environment.

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https://doi.org/10.1016/j.clrc.2026.100468
Received 3 April 2026; Received in revised form 13 July 2026; Accepted 13 July 2026
Available online 15 July 2026

1. Introduction

Circular Economy (CE), which is based on the principles of minimising the use of raw materials and reducing waste while maintaining the value of materials for an extended lifetime (Chartier et al., 2025; Erdiaw-Kwasie et al., 2024; Superti et al., 2021), acts as a basis for the current research on resource efficiency in the built environment (Aslanoğlu et al., 2026; Ellen MacArthur Foundation, 2013). Due to the strong connection between the impact of environmental challenges on economic and social values through the use of resources, the concept of circularity is viewed as a multidimensional transition rather than a technological solution (Kayaçetin et al., 2026). To ensure the creation of sustainable and resilient cities in terms of the use of resources, the concept of circularity acts as a dynamic system that combines innovation, regulatory frameworks, and cooperative tools (Fratini et al., 2019). The discussion on the concept of circularity is wide-ranging, with concepts and practices often scattered across various disciplines such as engineering, architecture, urban planning, economics, policy (Finamore and Oltean-Dumbrava, 2025), and different scales of the built environment (Li et al., 2017).

This fragmentation stems not only from the methodological inconsistencies to date but also from the scattered and disorganised nature of knowledge, where information is still treated separately by discipline, sector, and actor group (Li et al., 2025; Magnano et al., 2024). Such a fragmentation slows down the effective transfer of knowledge, limits inter-study comparability, and impedes coherent, cumulative frameworks for circularity research and practice. Hence, it undermines long-term CE planning (Agboola, 2026). The challenges of circularity, particularly in the built environment, require a systems-level integration capability that connects environmental, social, technological, and economic dimensions (Eikelenboom et al., 2021; Evertsen and Knotten, 2024). Although there has been an ever-increasing salience of circularity in policy agendas and the research literature, knowledge associated with the principles of the circular economy remains inconsistent in depth and varies across people (Velenturf and Purnell, 2021). The implementation of the CE is fundamentally hindered by knowledge asymmetry, a state of fragmentation where specialised technical expertise is isolated from normative public perspectives. This disciplinary and sectoral divide creates diverse knowledge levels, preventing the systemic integration required for a successful transition (Li et al., 2025; Magnano et al., 2024). Compounding this fragmentation is an overconfidence bias, or a calibration gap, where actors with lower objective proficiency consistently overestimate their understanding of circularity. This is not merely a deficit of information, but a metacognitive failure; as Senge et al. (2007) illustrate, actors are often unaware of the depth of the systemic requirements of their roles, perceiving circularity through an intuitive, experiential lens that masks a profound lack of technical grasp. To address these barriers, this study adopts a learning progression framework, termed the knowledge ladder. This trajectory rejects the simplistic assumption that circularity literacy is a linear accumulation of facts. Instead, following Zwiers et al. (2020), it is defined as a performed competence that structures action and informs decision-making. Mapping this ladder requires recognising that shifting from normative, experiential awareness to systemic, technical proficiency is a developmental process. As evidenced by Vrontissi et al. (2023), even advanced educational systems often struggle to bridge the gap between theoretical knowledge and practical competency, highlighting the urgent need for diagnostic tools that can empirically map these transitions.

Circular knowledge no longer follows the linear pattern in which understanding increases from lower to higher levels, but rather that of selective knowledge, with some knowledgeable actors possessing in-depth knowledge on a specific tool or strategy, but lacking holistic knowledge. For example, a study conducted by (Senge et al., 2007) found that some actors are not aware of the role they are expected to undertake (Dagilienė et al., 2021). This shows the lack of understanding that broader systemic changes are required for a complete transition to circularity. This has created a fragmented cognitive space where the notion of circularity is understood differently based on professional, institutional, and socio-educational differences. Honsa et al. (2025) examine the potential of instruments such as living labs to serve as platforms for connecting knowledge that was previously confined to isolated actors (Bulkeley et al., 2019), while also emphasizing that this is particularly challenging in the context of circularity due to the concept's broad and diffuse meaning. Expert knowledge is typically specialised and domain-specific, whereas public knowledge of circularity is more experiential and derived from personal experience, media, and informal learning. Therefore, raising awareness, altering attitudes, and encouraging actions that help mitigate and adapt to environmental change are all part of the complex CE strategies (Agboola, 2026). The transition from increased awareness into behavioural implementation was discussed in the works of Wojnarowska et al. (2026) and Anderluh et al. (2025) whom identified knowledge as the foundation that gradually transforms into attitude formation, perceived ability, behavioural intention and finally actual practice. The transition from awareness to implementation depends on competence, motivation, and repeated practice. Although less specialised than expert knowledge, public knowledge remains critical for the acceptance of CE policies.

1.1. Current state of CE knowledge

The co-existence of the different forms of knowledge is likely to lead to asymmetry in decisional power in relation to public participation in decision-making processes. In addition, public participation regarding circularity is largely based on expert-informed narratives and is likely to be more passive or symbolic than participatory (Freitas, 2012; Ortega Alvarado and Pettersen, 2024). On the other hand, the public's lack of understanding about systemic circularity is likely to affect public support for circularity, thereby creating less motivation for the sector or public authorities to adopt more ambitious paths towards circularity. As Zwiers et al. (2020) highlighted, practices and knowledge are fundamentally linked. In the same study, they emphasized that knowledge is not merely theory, but also guides practice, since knowledge shapes and prestructures actions. Perceived as an essential skill, performed knowledge can be viewed as a literacy to comprehend, characterise, and realise the change in circularity through methods and strategies (Zwiers et al., 2020). This conceptual model implies that performed knowledge requires strategies that are both standardised and contextualised. Although knowledge enables action, effective implementation depends on formal structures that translate individual literacy into systemic practice, which varies across local contexts.

Although ISO 59004:2024 (International Organization for Standardization, 2024) and related standards (ISO 59020:2024) provide an international technical reference for circularity practices, national knowledge disparities remain influenced by differences in regulations, policy development, and education systems. Countries integrating circular economy into education, professional training, and public communication tend to develop more comprehensive knowledge bases, highlighting how national contexts shape circularity specialisation. In the case of Türkiye, circularity has mainly been disseminated by government initiative on the zero-waste concept and a follow-up regulation until the National Circular Economy Strategy and Action Plan was published in 2025 (Ministry of Environment, Urbanization and Climate Change, Republic of Türkiye, 2025). In this plan, there are several steps to integrate CE training in the architecture-engineering curriculum and lifelong learning institutions. However, there is a lack of comprehensive education programmes dedicated to/including CE theory or practice. Consequently, the adoption and implementation of CE in several sectors is significantly low (Salgin et al., 2025). The current state of higher education in Poland faces a gap between the theoretical need for circular economy education and the level of awareness among students (Łuka et al., 2025). While education is seen as a crucial element in the transition from a linear economy to a circular economy, the current level of education is considered superficial and insufficient to facilitate this change. Educational campaigns are generally superficial, limited in scope, and fail to target diverse groups of producers and consumers (Łuka et al., 2025). Belgium, similarly to other European countries (Vrontissi et al., 2023), has extensive experience integrating circularity into higher education through permanent courses, summer schools, and workshops (Vrontissi et al., 2023). However, research indicates that circularity experts in the governmental and business sectors still report gaps in competencies, particularly in business models and the economic dimensions of environmental and ecological issues (Janssens et al., 2021).

Understanding circularity knowledge across the public–expert spectrum is critical for identifying leverage points that facilitate circular transitions. Knowledge shapes perceptions of feasibility, risks, value, and responsibility, influencing policy acceptance, market viability, and transition dynamics. Closing knowledge gaps therefore requires not only increasing knowledge but also structuring, translating, and contextualising it to improve its clarity and transferability across stakeholder groups.

1.2. Aims and objectives

The primary aim of this study is to advance the understanding of circularity knowledge in the built environment by developing a psychometrically validated diagnostic instrument and analyzing the structural determinants of knowledge across diverse stakeholder groups and national contexts. To address aforementioned gaps in understanding systematically, this study undertakes an investigation of circularity knowledge from both expert and general public groups through the collection of empirical material from six European countries, namely, the Netherlands, Belgium, Poland, Romania, Italy and Türkiye. The countries were chosen to offer a representation of diverse regulatory systems, levels of advancement in CE strategies, and educational systems, allowing for a better understanding of not just differing but also varying structures of such knowledge. The research methodology comprised two primary phases: the creation and psychometric validation of a dedicated circularity knowledge assessment instrument, followed by a comparative assessment of literacy patterns across six European countries.

The study pursues the following research objectives:

- **Instrument development and validation:** To design, psychometrically test, and validate a 25-item assessment tool capable of measuring circularity knowledge, ensuring reliability across the environmental, economic, social, technical, and managerial domains.
- **Comparative literacy analysis:** To quantify and compare circularity knowledge levels across both general public and expert groups, using a six-country sample (The Netherlands, Belgium, Poland, Romania, Italy, and Türkiye) to represent a wide spectrum of regulatory and educational maturity in CE strategies.
- **Identification of knowledge determinants:** To systematically analyze how demographic and professional factors shape individual circularity literacy, utilizing an IRT framework to map the knowledge ladder effect.
- **Strategic application:** To interpret findings through the lens of knowledge asymmetry and overconfidence bias, providing evidence-based recommendations for curriculum reform, policy implementation, and stakeholder engagement strategies (e.g., Urban Living Labs) to bridge the identified knowledge gaps.

2. Methodology

2.1. Design and ethics

For the development and validation of the Built Environment Circularity Knowledge Test, a step-by-step procedure was followed in line with the criteria stated by Consensus-based Standards for selection of health Measurement INstruments (COSMIN) (Mokkink et al., 2010). The development consisted of four phases: 1) development of the conceptual basis; 2) conceptualisation and item generation; 3) qualitative validation and pilot testing; 4) psychometric validation: testing structural validity and item functioning characteristics (Fig. 1).

Before the start of data collection and recruitment, the UrbanCoLLaR consortium obtained a *Certification of Ethical Acceptability for Research Involving Human Subjects* from the director of the Ethics Committee at the National University of Political Studies and Public Administration (SNSPA) on 23 May 2022. The study was conducted in accordance with the principles of the Helsinki Declaration of Human Rights.

2.2. Phase 1 and 2: Conceptual basis, conceptualisation, and item generation

In the first step, the aim was to establish a robust conceptual and theoretical foundation for the Circularity Knowledge Questionnaire. This foundation was informed by a systematic literature review of circularity assessment indicators and frameworks in the built environment (Li et al., 2025), which highlights the multidimensional nature of circularity and the fragmentation of existing measurement approaches. The review identified environmental, economic, social, technical, and managerial dimensions as key pillars of circularity assessment, underscoring the need for an instrument that captures knowledge across these domains rather than focusing on a single aspect. Furthermore, there is a need to harmonize existing circularity frameworks, which currently remain fragmented, rather than introducing additional alternatives.

The questionnaire was refined through expert co-creation (Aslanoğlu et al., 2026), ensuring alignment of the construct, target population, and intended application. The result of this phase was a shared conceptual

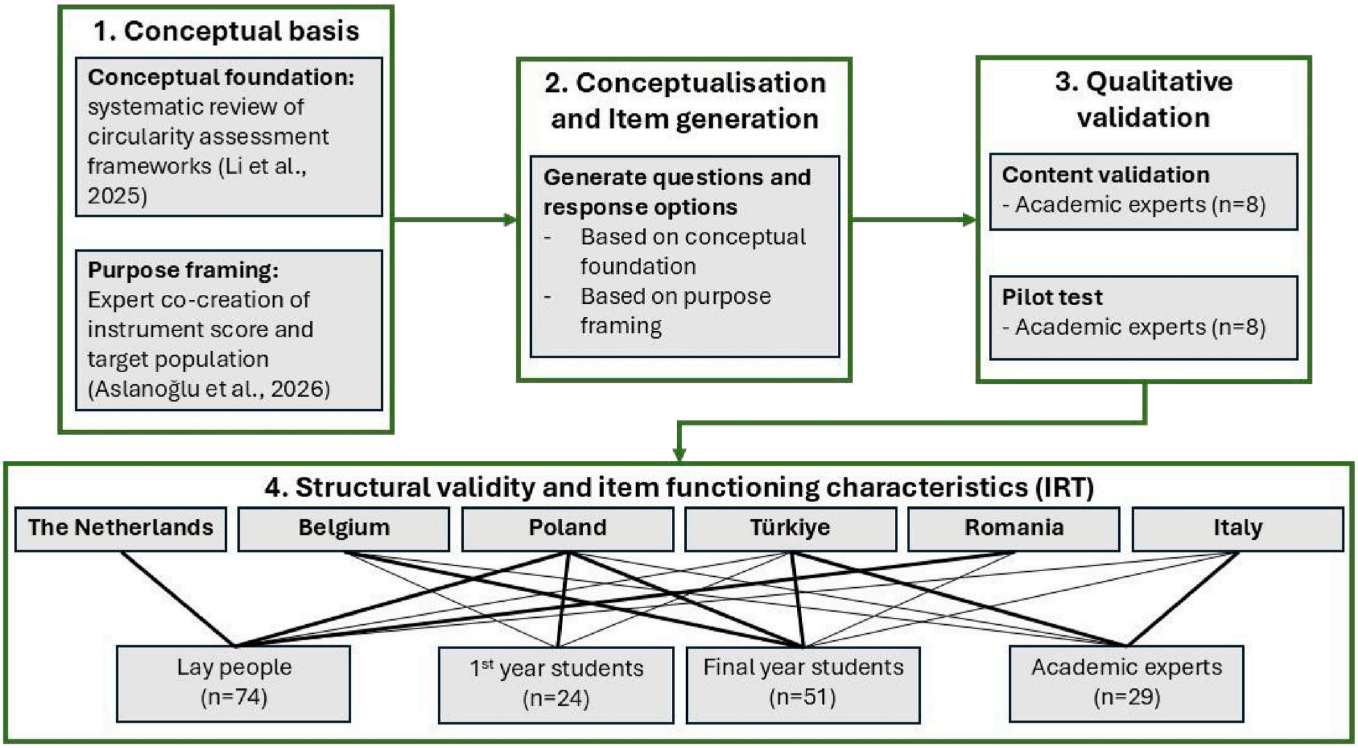

Fig. 1. Development and validation steps of the Built Environment Circularity Knowledge Test.

model defining what circularity knowledge entails and which knowledge areas are essential to measure. In the second step, this conceptual model was translated into a structured item pool through systematic conceptualisation and item generation. Questions and response options were developed directly from the established conceptual framework and the agreed purpose framing. Item development followed psychometric principles, distinguishing between knowledge-based constructs and attitudinal or behavioral constructs. Knowledge items were developed with objectively correct responses for Item Response Theory analysis, enabling differentiation of circularity knowledge levels. The iterative, expert-informed process ensured alignment with defined circularity domains, resulting in a conceptually coherent questionnaire. The instrument consists of 25 knowledge items, scored using a partial-credit approach, covering five domains: environmental, economic, social, technical, and managerial (Appendix A). IRT-based metrics, specifically the SEM, provides a more rigorous assessment of reliability. These metrics reflect the precision of the estimates across the continuum of latent ability, allowing to evaluate how effectively the 25-item instrument distinguishes between different levels of circularity knowledge. The instrument was validated through content validation, pilot testing, structural validation using IRT, and cross-national measurement invariance testing.

2.3. Phase 3: qualitative validation and pilot testing

Content validity was assessed using the structured approach described by Lynn (1986). A panel of eight international experts from the Urban-CoLLaR consortium participated in the validation process. The panel consisted of researchers and practitioners with expertise in urban circularity, sustainability, and the built environment. Experts were invited to independently rate the relevance of each questionnaire item on a four-point Likert scale (1 = not relevant at all, 2 = not relevant, 3 = relevant, 4 = extremely relevant).

For each item, the Item-level Content Validity Index (I-CVI) was calculated as:

Table 1
Known group respondents per country.

	Lay people	1st year students	Final year students	Academic experts
the Netherlands (n = 11)	11	0	0	0
Belgium (n = 21)	0	3	13	5
Poland (n = 58)	12	18	22	6
Türkiye (n = 25)	2	1	13	9
Romania (n = 51)	49	0	2	0
Italy (n = 12)	0	2	1	9
Total (n = 178)	74	24	51	29

$$I-CVI = \frac{N_{relevant}}{N_{total}}$$

Where $N_{relevant}$ is the number of experts who rated the item as 3 or 4 on the four-point scale, and N_{total} is the total number of independent experts who rated the item. Although Lynn (1986) suggests a minimum *I-CVI* of 0.78 for item retention, all items scoring below full agreement were discussed by the consortium.

Following content validation, the same eight experts pilot-tested the questionnaire to evaluate clarity, comprehensibility, usability, and item interpretation. Structured qualitative feedback identified ambiguous, redundant, overly complex, and conceptually overlapping items.

2.4. Phase 4: Participants and data collection

A purposive sampling strategy was employed to ensure a broad distribution of circularity knowledge, a prerequisite for robust Item Response Theory (IRT) parameter estimation and the mapping of the latent trait. To achieve this diversity, participants were recruited from four distinct tiers of expertise, ranging from laypeople to subject-matter specialists (Table 1). The baseline level of knowledge was captured through a sample of citizens recruited from the general public. This was supplemented by a cohort of novice learners, consisting of first-year undergraduate students enrolled in circularity-related programmes such as 'Civil Engineering Technology', 'Environmental Sciences and Design', and 'Sustainable Engineering'. To represent more advanced levels of proficiency, final-year students and postgraduate researchers were included, while the upper benchmark of the latent trait was established by recruiting academic experts and senior researchers with a proven track record in CE research. All of the students had training and lectures on CE.

Data were collected online using the 25-item instrument, with informed consent obtained from all participants. The final sample size was determined to ensure sufficient power for the estimation of the Generalized Partial Credit Model (GPCM). By including such a heterogeneous sample, the study aimed to ensure that the item difficulty thresholds (d) and discrimination parameters (a) were accurately estimated across the entire spectrum of the latent knowledge scale, from basic awareness to high expertise.

2.5. Phase 4: Item Response Theory modelling

The internal structure and psychometric properties of the 25-item instrument were examined using Item Response Theory (IRT). Owing to the scoring procedure of the multiple-response items, where correct options were awarded $+1$, incorrect options -1, and total item scores were bounded below at 0, the resulting item scores were treated as ordinal and polytomous. Accordingly, the Generalized Partial Credit Model (GPCM) (Muraki, 1992) was applied, as this model is appropriate for ordered response categories and allows item discrimination parameters to vary, thereby accommodating differences in how well items are able to distinguish between respondents with different levels of knowledge.

All analyses were conducted in R (version 4.5.1) using the *mirt* package (Chalmers, 2012). Before model estimation, core IRT assumptions were evaluated. Unidimensionality was assessed using exploratory factor analysis for categorical data, with particular attention to the presence of a dominant first factor, while local independence was examined using the Q_3 statistic to ensure that residual correlations between item pairs were negligible after conditioning on the latent trait. Item parameters were estimated using Marginal Maximum Likelihood (MML), yielding discrimination parameters (a) and threshold parameters (d) for each item. Global model fit was evaluated using the M_2 statistic and the Root Mean Square Error of Approximation (RMSEA), with values below 0.06 interpreted as indicative of good fit. Item-level fit was assessed using the $S\text{-}X^2$ statistic. Latent knowledge levels (θ) were estimated using the Expected A Posteriori (EAP) method to enable comparisons across respondent groups (citizens, students, and experts). An Item Person Map (Wright map) was constructed to visualise the correspondence between item difficulty thresholds and the distribution of respondent abilities, and Category Response Curves (CRCs) were inspected for each item to evaluate the functioning and ordering of the partial credit categories.

2.6. Cross-national Comparison and measurement invariance

To compare knowledge levels across the six participating countries, a Multiple-Group IRT (MG-IRT) framework was employed. This approach allows for the estimation of group-specific latent trait distributions while simultaneously identifying potential differences in item functioning across national contexts, thereby placing all respondents on a common latent scale. The composition of respondent cohorts (citizens, students, and experts) differed across countries, with some cohorts not represented in every national sample. To accommodate this imbalance, a linked design was adopted, allowing the national samples to be placed on a common metric despite differences in cohort composition. In this design, item parameters (discrimination and threshold parameters) were initially constrained to be equal across countries. Respondent types present in multiple countries, notably students and citizens, functioned as anchor groups, aligning the latent scales and permitting valid comparisons of mean knowledge levels (θ) across countries, even in the absence of certain cohorts in specific jurisdictions.

Before interpreting cross-national differences, measurement invariance was evaluated to ensure that the 25 items operated equivalently across geographical contexts. Metric and scalar invariance were assessed by comparing a constrained model, in which item parameters were held equal across countries, with a freely estimated model using Likelihood Ratio Tests and changes in global fit indices (such as RMSEA). In addition, Differential Item Functioning (DIF) was examined using Wald tests; items were flagged for DIF if they exhibited significantly different discrimination or threshold parameters in one country relative to others, conditional on the same underlying knowledge level. Items displaying substantive DIF were released and estimated uniquely for the affected country, thereby achieving partial invariance while preserving the validity of the common latent scale. Once full or partial invariance had been established, latent mean knowledge levels were estimate for each country. For model identification, the mean and variance of the reference country were fixed to 0 and 1, respectively, while the latent means of the remaining countries were freely estimated and compared using Wald tests.

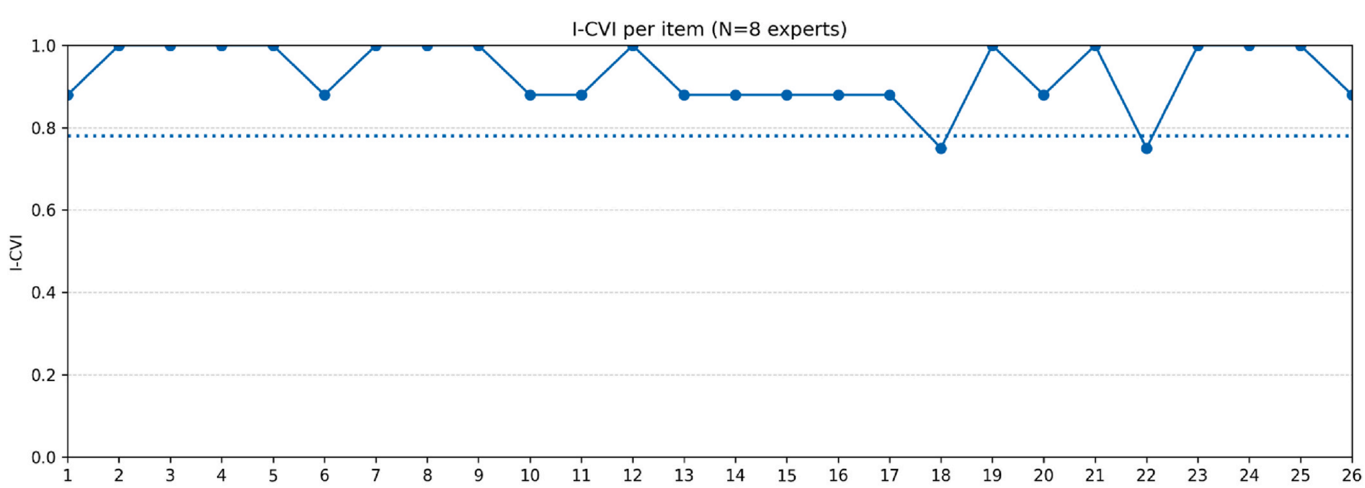

Fig. 2. Item-level content validity index (I-CVI) scores for the 26 knowledge test items rated by experts (n = 8). The dotted horizontal line indicates the recommended minimum acceptability threshold (I-CVI = 0.78).

3. Result

3.1. Qualitative validation

Fig. 2 presents the *I-CVI* scores for the 26 knowledge items resulting from phases 1 and 2, rated by the expert panel (n = 8).

Of the 26 items, 13 achieved full expert agreement, resulting in an *I-CVI* of 1.00. Eleven items showed strong agreement with an *I-CVI* of 0.88, meaning 7 out of 8 experts rated these items as relevant. Two items fell below Lynn's (Lynn, 1986) recommended acceptability threshold of 0.78, with an *I-CVI* of 0.76. All 13 items with an *I-CVI* lower than 1.00 were subsequently discussed in conjunction with the qualitative feedback collected during pilot testing. This combined evaluation focused on clarity, conceptual alignment with the circularity knowledge construct, and coverage of the domains identified by Li et al. (2025). The discussion informed targeted revisions and final decisions on item retention, modification, or exclusion, ensuring that the resulting questionnaire balanced expert consensus with practical interpretability. Only item 26 *"Which of the following strategies help raise awareness about Circular Economy practices in the built environment?"* was excluded. The expert panel concluded that this item did not sufficiently align with the intended knowledge construct nor with the substantive circularity domains identified in Li et al. (2025).

3.2. Psychometric evaluation of the Circularity Knowledge Test

The psychometric evaluation followed a stepwise procedure, beginning with assumption checks and proceeding to model fit, item functioning, measurement precision, targeting, and interpretability.

3.2.1. Assumption checks

Unidimensionality was examined using exploratory factor analysis for categorical data (Fig. 3).

The first factor displayed a dominant eigenvalue of 9.78, substantially exceeding the first eigenvalue obtained from simulated data (0.85). The ratio between the first and second eigenvalue (7.71) further confirmed the presence of a strong primary latent dimension. Together, these results provide clear empirical support for modelling the instrument using a unidimensional IRT framework.

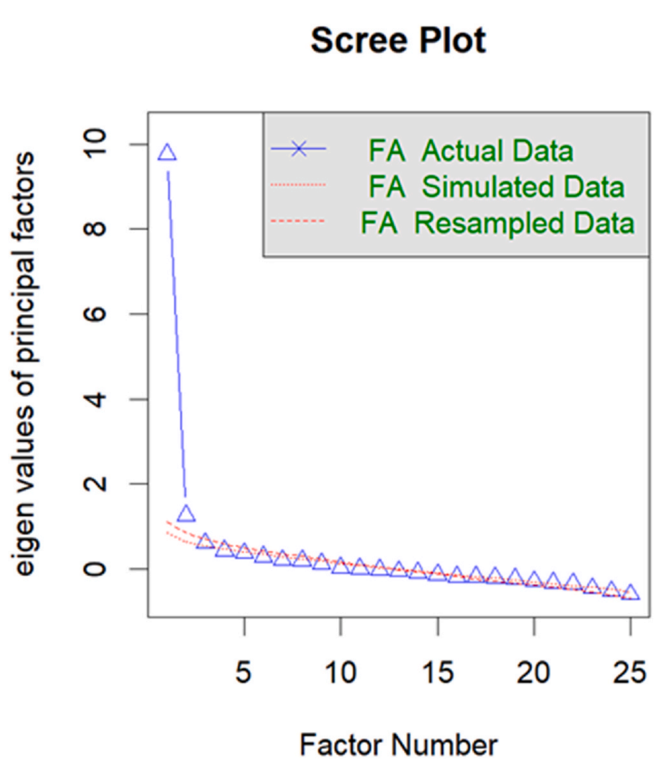

Fig. 3. Scree plot of the Circularity Knowledge Questionnaire.

Local independence was evaluated using the Q_3statistic, which assesses residual correlations between item pairs after conditioning on the latent trait (θ). The mean Q_3value was −0.034, indicating that, on average, no systematic local dependence remained once the primary dimension of knowledge was accounted for. A small number of item pairs exceeded the commonly applied threshold of 0.20 (Q1–Q17: $Q_3 = 0.254$; Q23–Q24: $Q_3 = 0.242$). These instances were isolated and did not form coherent clusters suggestive of secondary dimensions or local item dependence. Consequently, the assumption of local independence was considered sufficient for the application of the GPCM.

Monotonicity was evaluated using both parametric and non-parametric approaches. Visual inspection of the Item Probability Functions (Appendix B) confirmed that, for all polytomous items, response categories were ordered as intended: the probability of endorsing higher categories increased monotonically with higher levels of θ. This pattern was corroborated by a non-parametric Mokken Scale Analysis (Sijtsma and Van Der Ark, 2017). Across all 25 items, no significant violations of monotonicity were detected ($z_{sig} = 0$, $p > .05$). Although item Q8 exhibited a relatively low scalability coefficient ($H_i = 0.07$), it did not demonstrate statistically significant violations that would undermine the measurement model. Q8 was retained because it captures a key aspect of circularity knowledge, prioritisation within the waste hierarchy, at the expert level, which is not covered by other items. In addition, some respondents selected multiple options for items intended as single-best-answer questions (including Q8). Although partial credit scoring was applied, this may have attenuated discrimination. Therefore, instructions have been revised to explicitly indicate that only one answer should be selected for these items (Q1, Q3, Q8, Q20). Taken together, the low discrimination of Q8 is most likely due to its extreme difficulty and limited representation of high-ability respondents, rather than a lack of conceptual relevance, and was therefore retained. These findings indicate that the instrument reliably differentiates respondents across the full continuum of circularity knowledge.

3.2.2. Global model fit

Following confirmation of the core IRT assumptions, the global fit of

Table 2
Item parameters estimates for the Circularity Knowledge Test under the GPCM.

Item	Discrimination (α)	Threshold 1 (β_1)	Threshold 2 (β_2)	Threshold 3 (β_3)	Item Fit (p.S-X^2)
Q1	0.880	0.392	-	-	0.489
Q2	1.003	−2.064	−0.726	0.106	0.138
Q3	0.931	−0.087	-	-	0.625
Q4	0.537	0.753	1.209	-	0.507
Q5	0.597	−2.167	−0.715	1.336	0.199
Q6	0.511	−0.963	0.042	−0.785	0.016*
Q7	0.572	−3.202	−0.452	1.738	0.098
Q8	0.271	3.949	-	-	0.318
Q9	1.269	−2.396	−0.454	0.447	0.000*
Q10	0.825	−1.078	−0.029	1.467	0.077
Q11	1.853	−1.572	−0.558	0.547	0.142
Q12	1.119	−2.044	−0.321	−0.006	0.006*
Q13	1.498	−2.161	−0.605	0.274	0.039*
Q14	1.241	−1.630	−0.757	0.732	0.131
Q15	1.636	−0.871	−0.564	0.336	0.355
Q16	1.141	−1.054	0.180	-	0.045*
Q17	1.468	−1.066	−0.369	0.387	0.025*
Q18	2.240	−1.444	−0.574	−0.039	0.033*
Q19	1.938	−1.663	−0.969	−0.219	0.064
Q20	1.182	−0.112	-	-	0.045*
Q21	1.541	−1.097	−0.478	1.092	0.225
Q22	0.925	−2.085	0.090	0.950	0.003*
Q23	0.505	0.057	0.856	-	0.380
Q24	1.277	−0.202	−0.702	-	0.035*
Q25	1.182	−2.047	−0.574	−0.158	0.016*

the GPCM was evaluated using the M_2 statistic and the Root Mean Square Error of Approximation (RMSEA). The model showed good overall fit to the data ($M_2 = 394.98$, $df = 237$, $p < .001$). Although the RMSEA of 0.061 marginally exceeded the strict 0.06 cut-off, it remains indicative of adequate fit when interpreted alongside the Comparative Fit Index (CFI = 0.966) and Tucker Lewis Index (TLI = 0.962), both of which comfortably exceed the recommended 0.95 criterion. Taken together, these indices justify proceeding with the examination of item-level parameters and the derivation of latent trait scores.

3.2.3. Item parameters and item functioning

Item discrimination parameters (α), reflecting the capacity of each item to differentiate between respondents with differing levels of θ, varied substantially across the scale (Table 2).

Discrimination ranged from 0.271 (Q8) to 2.240 (Q18). The majority of items demonstrated strong discriminative power ($\alpha > 1.0$), with Q18 ($\alpha = 2.240$), Q19 ($\alpha = 1.938$), and Q11 ($\alpha = 1.853$) providing the most precise differentiation along the latent continuum.

In contrast, Q8 exhibited very low discrimination ($\alpha = 0.271$), indicating that it contributes minimally to measurement precision for most respondents. These differences are visually reinforced by the Item Information Functions (Appendix C): high-discrimination items such as Q18 and Q19 display sharp, pronounced information peaks, whereas Q8 shows an almost flat information curve across the θ-range.

Threshold parameters (β), indicating the level of θ at which respondents have a 50% probability of transitioning to a higher response category, were well distributed across the latent trait. Most thresholds were located between −2.0 and + 1.5 standard deviations from the mean. Q8 emerged as a clear outlier, with a primary threshold of 3.949, indicating that it targets respondents at the extreme upper end of the knowledge distribution (Table 2).

Visual inspection of the Item Probability Functions (Appendix B) confirmed that response categories for all polytomous items were ordered correctly. Successive categories (P1–P4) peaked at increasing levels of θ, validating the partial credit scoring structure. Items with steep category transitions, such as Q18 and Q11, visually mirror their high discrimination estimates, whereas the shallow profile of Q8 reflects its limited measurement contribution.

3.2.4. Item fit and measurement precision

Item discrimination parameters (α), reflecting the capacity of each item to differentiate between respondents with differing levels of θ, varied substantially across the scale (Table 2). Discrimination ranged from 0.271 (Q8) to 2.240 (Q18). The majority of items demonstrated strong discriminative power ($\alpha > 1.0$), with Q18 ($\alpha = 2.240$), Q19 ($\alpha = 1.938$), and Q11 ($\alpha = 1.853$) providing the most precise differentiation along the latent continuum.

Item-level fit was evaluated using the $S\text{-}X^2$ statistic, where a significant p-value ($p < .05$) indicates deviation between observed and model-predicted response patterns. Several items (for instance, Q9, Q12, Q22) exhibited statistically significant misfit (Table 2). These items were nevertheless retained for three reasons. First, global model fit indices remained robust (CFI = 0.966; RMSEA = 0.061). Second, visual inspection of the Item Probability Functions (Appendix B) showed coherent and monotonic category functioning. Third, these items were judged essential for maintaining the content validity of the knowledge construct. A localized misfit of this kind is common in longer instruments and does not necessarily compromise the overall utility of the scale (Embretson and Reise, 2013).

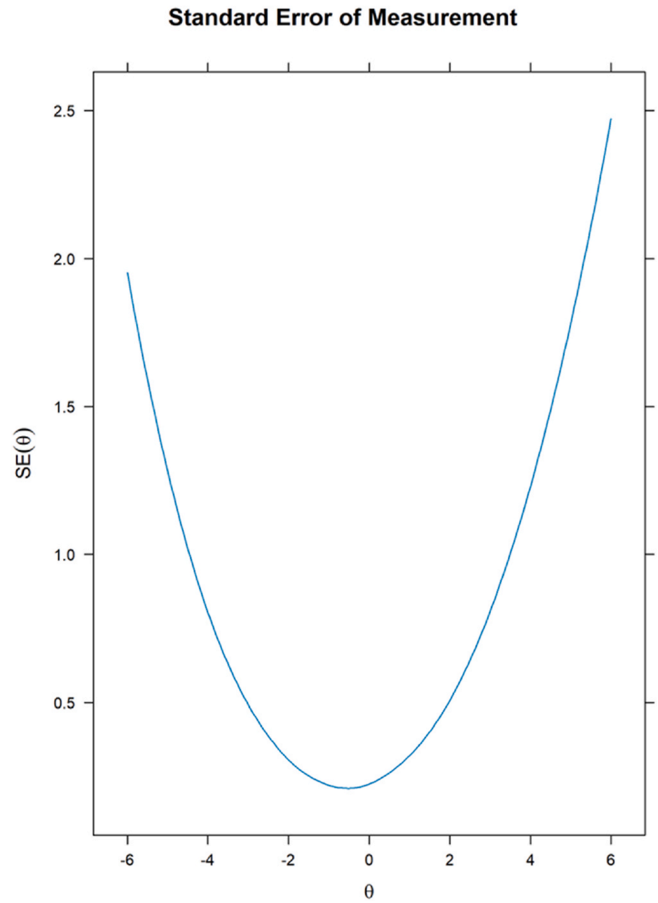

Fig. 4. Standard error of measurement (SEM) function.

Measurement precision across the latent continuum was examined using the Standard Error of Measurement (SEM) function (Fig. 4).

The instrument provides its highest precision (lowest SEM ≈ 0.22) for respondents with slightly below-average to average knowledge levels, specifically where θ lies between −2 and 0. As expected, measurement error increases toward the extremes of the distribution ($\theta < -4$ or $\theta > +4$). This pattern confirms that the instrument is optimally calibrated for its intended target population.

3.2.5. Targeting and instrument calibration

Targeting was assessed using the Wright Map (Fig. 5), which displays the distribution of person parameters (left) and item difficulties (right) on a shared logit scale.

The map reveals strong correspondence between the two distributions: the majority of item difficulties are located between −1.5 and + 1.0 logits, coinciding with the densest region of the respondent distribution. This alignment provides empirical evidence for optimal targeting of the Circularity Knowledge Test. The instrument effectively spans the latent trait range without pronounced floor or ceiling effects, indicating that it is neither too simple for high-performing respondents nor too demanding for those with emerging knowledge.

A notable exception is item Q8, positioned at approximately +4.0

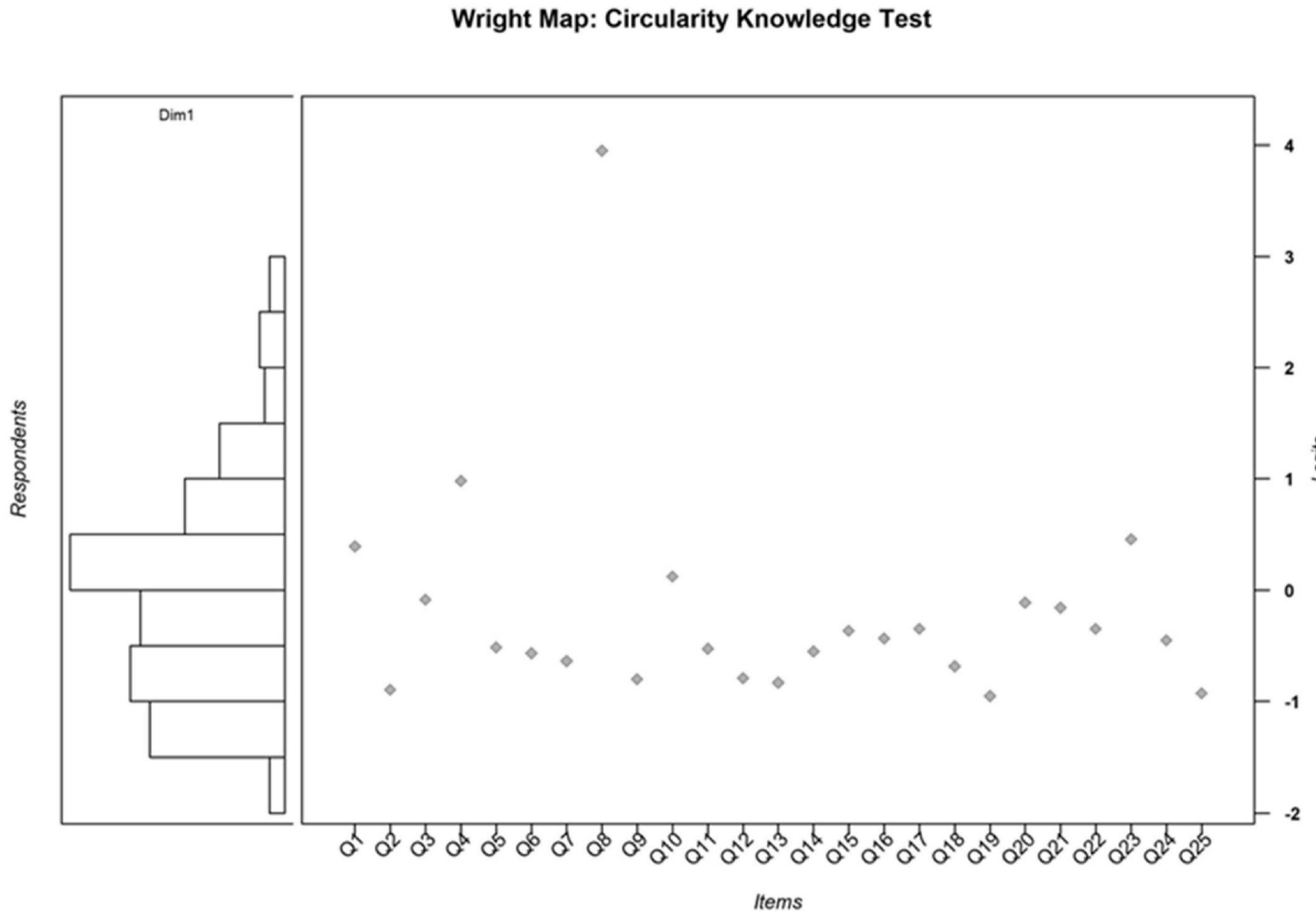

Fig. 5. Wright map (Item-person map) of the circularity knowledge test.

Table 3
Normative group comparisons on Circularity Knowledge Questionnaire scores.

Norm group	N	Mean score (±SD)	Threshold score	Cohen's d
Laymen	73	34.0 ± 12.2	-	-
1st year students	24	35.0 ± 13.6	34.5	0.08
Final year students	51	38.4 ± 11.1	36.8	0.28
Experts	30	49.6 ± 9.91	44.3	1.05

logits. This confirms its status as an extreme outlier, functioning as an "expert-level" item that discriminates only among respondents at the upper tail of the knowledge distribution. Conversely, items such as Q2, Q19, and Q25 occupy the lower end of the difficulty spectrum (approximately −1.0 logits), ensuring adequate precision for respondents with limited baseline knowledge.

Overall, the calibration results demonstrate that the Circularity Knowledge Test is well aligned with the ability distribution of the sampled population and provides a reliable measurement across the range most relevant for empirical and educational applications.

3.2.6. Usability and interpretability

To facilitate the practical application of the Circularity Knowledge Test, norm references were established following the methodology applied by Dikken et al. (2016). A strong Pearson correlation ($r = 0.812$, $p < .001$) was found between the IRT-derived latent proficiency (θ) and the CTT-based raw scores (0–64), justifying the use of raw scores for benchmarking purposes. As illustrated in Table 3 and Fig. 6, the knowledge ladder remains visible across the expertise cohorts. While 'Laymen' and '1st Year Students' share a nearly identical baseline, significant progression is observed as students move toward graduation. The most substantial gap was identified between 'Final Year Students' and 'Experts' ($d = 1.05$), with a threshold score of 43.3 points. This threshold represents the critical cutoff point where a respondent's performance aligns more closely with professional expertise than academic proficiency. These findings demonstrate that the instrument is highly sensitive to the accumulation of circularity expertise throughout a professional career.

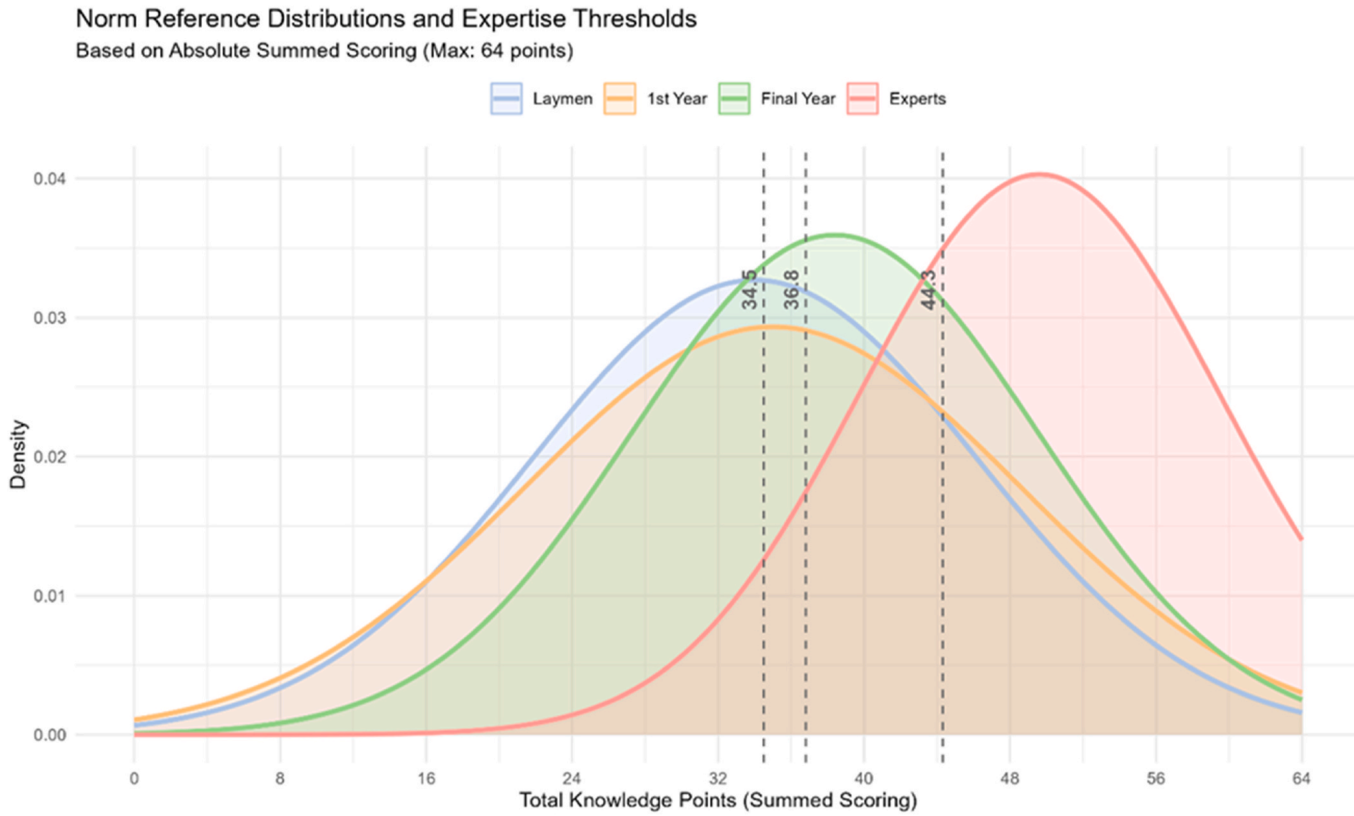

Fig. 6. Norm reference distributions and expertise thresholds for Circularity Knowledge scores.

3.3. Knowledge outcomes and Construct validation

3.3.1. Comparative analysis of expertise levels

Construct validity of the Circularity Knowledge Questionnaire was examined by comparing latent knowledge scores (θ) across the four predefined expertise groups. The results reveal a clear and systematic gradient in performance, forming a progressive knowledge ladder (Fig. 7) that aligns with theoretical expectations regarding educational and professional development.

Descriptive statistics indicate that lay participants ($M = -0.31$, $SD = 0.80$) and first-year students ($M = -0.18$, $SD = 1.07$) exhibit the lowest mean levels of latent knowledge. The modest difference between these two groups suggests that students at the onset of higher education possess a baseline level of circularity knowledge comparable to that of the general public.

A discernible educational gain emerges among final-year students ($M = -0.02$, $SD = 0.83$), who outperform their first-year counterparts. The most pronounced differentiation occurs at the expert level. Experts achieved substantially higher scores ($M = 0.92$, $SD = 0.93$) than all other groups. The increase in mean θ between final-year students and experts is nearly six times larger than the difference observed between the two student cohorts. This pattern indicates that while formal education contributes to foundational knowledge acquisition, professional engagement or specialised expertise in the field is associated with a markedly more advanced level of mastery.

The preservation of this ordered hierarchy provides strong evidence for the construct validity of the instrument: the Circularity Knowledge Test reliably differentiates between theoretically meaningful levels of expertise.

3.3.2. The role of professional experience

To further investigate determinants of circularity knowledge, a two-way ANOVA was conducted with expertise level and professional experience as factors and latent knowledge (θ) as the outcome variable. The analysis revealed a significant main effect of professional experience, $F(1,160) = 5.32$, $p = .022$, indicating that individuals with practical experience consistently outperform their inexperienced counterparts across all expertise levels.

Group means (Fig. 8) illustrate the compensatory effect of professional exposure. Most notably, experienced lay participants achieved a mean knowledge score ($M = -0.01$) that closely approximated that of final-year students without professional experience ($M = -0.08$). This convergence suggests that sustained engagement with circularity-related practices can partially substitute for formal educational progression in the development of domain-specific knowledge.

No significant interaction was observed between expertise level and experience ($p = .956$), indicating that the knowledge gain associated with professional exposure is uniform across the sample. Whether at the beginning of an educational trajectory or at an advanced expert level, professional experience confers a consistent increase in proficiency.

Fig. 7. Knowledge ladder: Validation of the Circular Knowledge Questionnaire.

These findings underscore the importance of integrating applied learning opportunities into educational pathways within the circular economy domain.

3.3.3. Meta-cognitive calibration

The relationship between objective knowledge (θ) and subjective self-assessment was examined to evaluate how participants' perceptions of their own expertise change in response to completing the test (Fig. 9). Across cohorts, the results reveal a systematic recalibration effect.

Among lay participants, pre-test self-assessments already show a clear positive association with objective knowledge, indicating that a basic level of calibration is present from the outset. After making the test, this relationship becomes even steeper, suggesting refinement and strengthening of calibration. A different starting point is observed among first- and final-year students. In both cohorts, the pre-test association is comparatively weak, implying limited alignment between perceived and actual knowledge. After completing the test, the slopes increase markedly, and the regression lines shift upward, indicating both improved calibration and greater confidence in self-assessment. The effect is strongest in first-year students, consistent with a substantial metacognitive adjustment in early-stage learners. Experts display a contrasting pattern: their pre-test calibration is already strong, but the

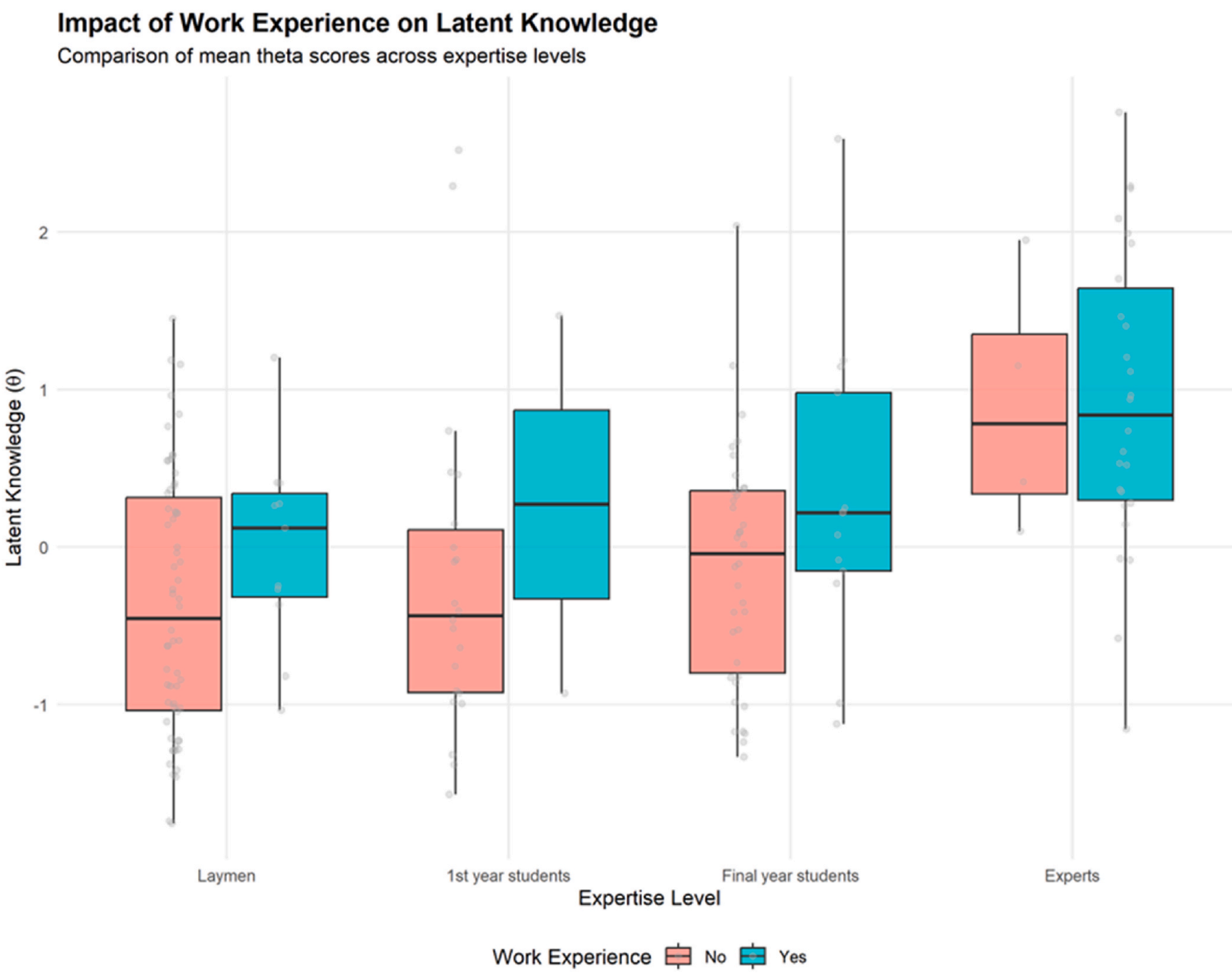

Fig. 8. The role of professional experience in latent knowledge acquisition.

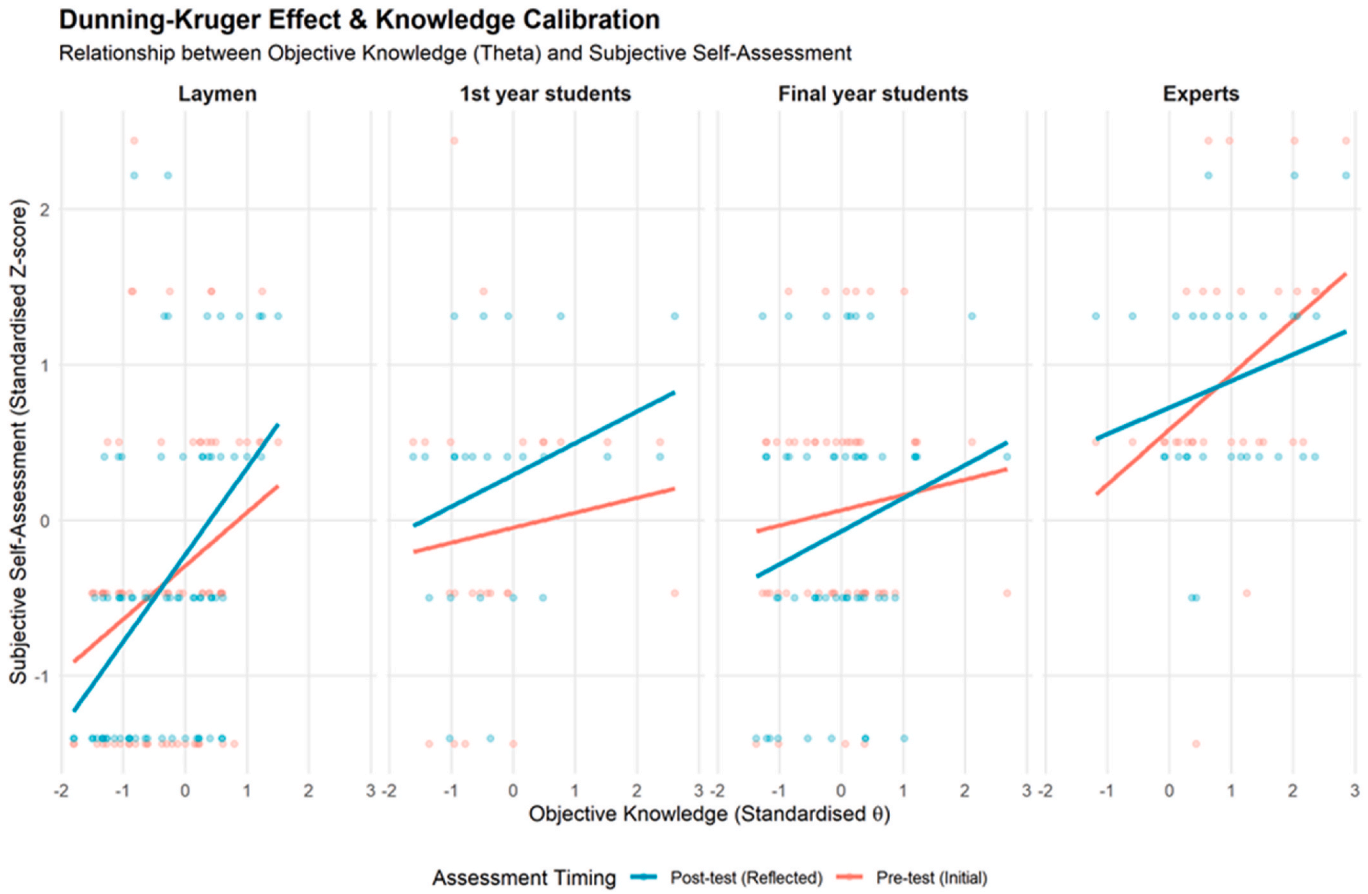

Fig. 9. *Meta-cognitive Calibration and the Dunning-Kruger Effect* (Kruger and Dunning, 1999).

post-test slope is slightly attenuated. This flattening is consistent with more cautious or conservative self-appraisal when confronted with demanding items, particularly at the upper end of the scale.

Fig. 9 shows that lay participants initially overestimate their understanding of circularity, but this effect diminishes after completing the questionnaire, indicating that the test functions as a metacognitive intervention by shifting participants from intuitive to more expert reasoning. This is particularly valuable in ULLs, where informed co-creation is essential. Overall, the questionnaire supports both knowledge assessment and expertise-dependent recalibration.

3.3.4. *Cross-national comparison*

To assess the robustness of the instrument across national contexts, latent knowledge scores (θ) were disaggregated by both country and expertise level (Fig. 10).

Given the heterogeneous distribution of participants across the six countries, this stratified presentation is essential. Comparisons are made within peer groups rather than relying on aggregated national means.

In every country where multiple expertise cohorts were represented, the internal knowledge hierarchy remained intact. Experts consistently outperformed students, who in turn scored higher than lay participants. The preservation of this ordered structure across diverse educational and professional environments, from vocationally oriented contexts to specialist professional samples, indicates that the instrument captures a stable and transferable construct of circularity knowledge.

The greatest cross-national variance is observed within the first-year student cohort. Secondary analysis revealed that this variation is primarily attributable to differences in academic entry level rather than national context. In Belgium and Italy, first-year samples consisted predominantly of Master-level students ($M^{Master1} = 0.96$), whereas the Polish sample comprised Bachelor-level entrants ($M^{Bachelor1} = -0.48$). A Welch two-sample *t*-test confirmed that this difference is statistically significant ($p = 0.039$).

This divergence diminishes over time, with no significant difference between Bachelor's and Master's students by the final year ($p = 0.361$), indicating convergence in circularity proficiency. These findings demonstrate that the Circularity Knowledge Test is a robust diagnostic tool for international comparison, preserving expected expertise hierarchies while detecting meaningful differences in educational entry levels.

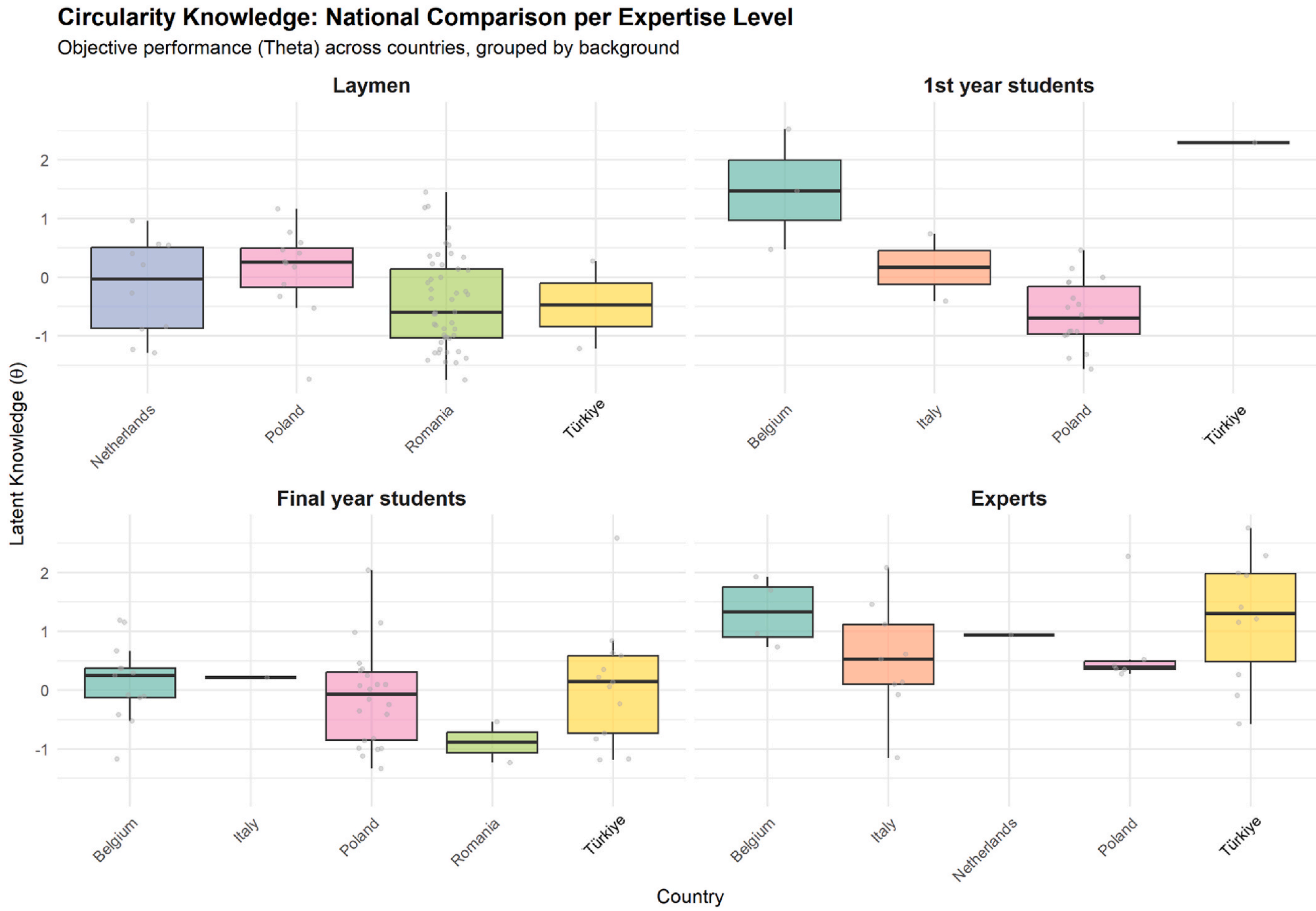

Fig. 10. Distribution of latent knowledge scores (θ) across countries and expertise levels.

4. Discussion

This study analyses circularity knowledge across the public–expert spectrum and six countries using a psychometrically validated IRT-based instrument. The findings show that circularity knowledge forms a permeable continuum rather than a public–expert dichotomy, highlighting that circularity proficiency requires systemic, holistic understanding. The knowledge ladder effect between the lay participants, the early-stage students, the advanced students, and the experts supports the notion of circularity knowledge accumulation along the lines of formal educational attainment and engagement in the field (Figs. 6 and 7) (Zwiers et al., 2020). Nevertheless, the limited knowledge gap between the lay participants and the first-year students implies that basic higher educational attainment does not necessarily equate to increased circularity literacy. The significant jump in knowledge between the final-year students and the experts supports the notion of the significant role of professional engagement and practice in the acquisition of circularity knowledge. The results clearly distinguish between circularity awareness and competence, providing a basis for designing CE strategies and educational programmes tailored to different knowledge levels.

Professional experience was a significant independent predictor of circularity knowledge across all expertise groups, benefiting both lay participants and experts. Notably, experienced lay participants achieved knowledge levels comparable to advanced students, suggesting that practical experience can partially substitute for early formal education in acquiring circularity knowledge. Furthermore, the effect of the extreme upper-end element (Q8) points to intergroup uncertainty. At the highest levels of competence, differentiation becomes difficult because, by the nature of expert knowledge, there is a shift from rule-based knowledge to context-based judgments. For the general public, however, this element has limited meaning. It has a certain symbolic significance as a means of defining the logical limits of expert thinking. The item-level results add additional detail to the interpretation of the results. While high-discrimination items were heavily linked to systemic, lifecycle-based reasoning, low-discrimination items were much more focused on simple familiarities or on existing narratives regarding the concept of circularity (Hillsley, 2025). Such findings suggest that what sets apart knowledgeable actors is not that they are familiar with the terminology, but rather that they are capable of reasoning on various scales, time horizons, and interdependencies (Player et al., 2023). From a policy perspective, these findings suggest that awareness campaigns, while potentially useful as a general tool, should be supplemented with a comprehensive systems-based understanding of these concepts that goes beyond simple awareness of a slogan or a single remedy (recycling, material substitution, etc.) (Keramitsoglou et al., 2023; Portus et al., 2024).

The results of the meta-cognitive calibration study provide a significant psychological layer to the discussion of the disparity of knowledge (Fig. 9). The low-knowledge groups were found to be poorly calibrated before taking the test, while the results of the post-test self-assessment were found to be significantly more calibrated. The fact that the low-knowledge groups were found to be poorly calibrated before taking the test, while the results of the post-test self-assessment were found to be significantly more calibrated, implies that tools designed to measure knowledge of circularity could be used to educate, not just diagnose. The fact that experts were found to be well-calibrated before taking the test, while the results of the post-test were found to be slightly more conservative, implies that tools designed to measure knowledge of circularity could be used to promote epistemological humility, even among experts. This is desirable, given the inherently complex nature of the circularity.

It is also important to note that there is some imbalance within the samples and cohorts in terms of size across the participating nations in the study, with a noticeably higher number of participants from Poland (n = 58) than in the case of the Netherlands (n = 11) and Italy (n = 12). Even though the use of the MG-IRT method has allowed for the stability of parameters across different populations through a linked design approach, these differences mean that the conclusions should be drawn carefully and cautiously because of the limitations imposed by such a design. The findings are not nationally generalisable but instead demonstrate the validity and performance of the instrument across different national contexts.

The cross-country analysis confirms the instrument's construct validity and measurement stability, supporting circularity knowledge as a transferable latent construct. Differences in first-year student knowledge were primarily explained by curriculum level (Bachelor's vs. Master's) rather than nationality, but disappeared by the final year, suggesting convergence through exposure to circularity curricula. These findings highlight the importance of curriculum integration and specialisation for harmonising circularity knowledge across countries, although socio-economic factors may still influence the pace of convergence. The pace of innovation in the circularity domain means that the content validity of this Built Environment Circularity Knowledge Test cannot be assumed to remain stable over time. Validity is contingent on the continued relevance of item content rather than on a fixed lifespan (American Educational Research Association, 2011; Messick, 1995). For rapidly evolving fields, the best practice is not to define a strict revision interval but to conduct periodic expert review before use in research, education, or professional assessment. As a pragmatic guideline, reassessment every 3–5 years is advisable, with earlier review warranted when substantial domain developments occur. Such ongoing scrutiny helps ensure that items remain aligned with contemporary standards and preserves the interpretability of test scores (Haynes et al., 1995; Kane, 2013). Even though it requires periodic expert review, this Built Environment Circularity Knowledge Test allows for a more objective distinction to be made concerning the diverse levels of circularity expertise, making it an empirical tool to determine the expertise of a person. Thus, it is a very powerful tool with regard to the composition of the panel of an expert committee, which is based on the expertise of the members.

An effective transition to circularity in the built environment requires shared decision-making among diverse stakeholders. Accordingly, training and experiential learning can serve as important leverage points for accelerating the transition. This also supports the governance argument that knowledge disparity between experts and non-experts cannot be attributed to informational deficits alone, and that knowledge disparity is structural and related to how circularity knowledge is constructed and used. Knowledge misalignment can slow adoption, distort risk perceptions, and reduce policy effectiveness. Non-experts may focus on short-term, visible risks while overlooking long-term environmental and social benefits, whereas experts often evaluate risks through systemic and lifecycle-based perspectives. As a result, policies based solely on expert knowledge may lack public support and be interpreted inconsistently, and stakeholder engagement may become symbolic rather than genuinely co-creative.

The results above strengthen the case for circularity transitions being contingent on knowledge architecture, rather than merely technological innovation or regulatory design. Three implications emerge from the leverage points:

1. Embedding in the curriculum is more important than early exposure, as shallow and disjointed early education yields little tangible benefit over the general public.
2. Practice-based learning is an extremely effective route, as professional exposure leads to significantly faster knowledge acquisition.
3. Assessment-driven reflection improves calibration, as systematic testing can help realign perceived and actual knowledge, enhancing the quality of stakeholder participation.

At the same time, the results provide a foresight toward the future use of the questionnaire; to quantify the precision of stakeholder (especially public and expert) contributions in participatory methods, including approaches such as the quintuple helix or Urban Living Labs (ULL). ULLs are frequently used in social and/or hybrid studies where innovation is expected via the interaction of different disciplines, cultures, and stakeholders. The questionnaire can support participatory methods by assessing stakeholder knowledge and tailoring engagement accordingly. In ULLs, it can diagnose knowledge levels at project outset, enabling coordinators to adapt co-creation activities. Groups with lower knowledge may benefit from alignment tools such as boundary objects and simplified circularity frameworks, whereas groups with higher knowledge can engage directly in complex systems discussions and decision-making. Such an observation is in line with Wojnarowska et al. (2026) and Anderluh et al. (2025), underlining that increased knowledge, either by profession or with awareness increase practices in workshops, can lead to a shorter process for implementation. Thus, ULL coordinators can use the diagnostic to adjust the complexity of their engagement process accordingly.

In practice, the questionnaire can provide preliminary insights into participants' knowledge, supporting ULL coordinators in forming appropriate stakeholder groups, planning activities, and designing tailored participatory methods. For example, such insights can help prevent mismatches between stakeholders and tasks, as well as ensure shared understanding and a common knowledge base during participatory processes, as highlighted by previous studies (Honsa et al., 2025). In education, the questionnaire can serve as a baseline tool for evaluating learning outcomes. Unlike existing circularity assessment frameworks that focus on environmental and technical outcomes, it captures knowledge, awareness, learning, and calibration, providing a complementary perspective on the cognitive and educational conditions underlying circularity.

As this study shows, the findings do not apply only to European education and regulatory institutions; rather, they are part of the process of building expertise in complex systems of CE. Scientists outside Europe will be able to reproduce this study using the same sampling method of selecting participants at different points on the expertise continuum. Thus, the questionnaire serves as an internationally applicable reference point for circular knowledge assessment.

5. Conclusion

This study presents the IRT-based development and cross-national validation of the Built Environment Circularity Knowledge Test, showing that circularity knowledge forms a continuum shaped by education and professional experience. The results imply that the circularity transitions depend not only on institutional or technological preparedness, but also on how the knowledge is distributed and structured among actor groups. Thus, a potential mismatch of knowledge depth, as opposed to knowledge deficiency, might be a principal source of resistance to all processes, including policy implementations. Professional collaboration environments, including living labs, represent effective opportunities for knowledge development across both expert and non-expert populations.

The findings are of fundamental importance in terms of policies and education. Based on the results, circularity transitions are highly dependent on the distribution of the actors' knowledge. Thus, policy communication needs to be adjusted according to the specific levels of proficiency of the target group members to avoid knowledge gaps resulting in active resistance. At the same time, the findings confirm the need to change the educational curriculum used today. Instead of implementing generalized sustainability courses, the higher education curriculum should be adjusted according to the particular cognitive thresholds in order to help the students make the transition from the normative to the systems level.

Finally, the Built Environment Circularity Knowledge Test may serve as a common tool for assessing stakeholder knowledge and informing engagement strategies. Although psychometrically robust, periodic review of its content validity is recommended given the rapid evolution of circularity. In ULLs, the instrument could support stakeholder mapping and tailored co-creation based on participants' knowledge profiles. Ultimately, it provides a foundation for bridging expert and public knowledge to support more inclusive and effective circular transitions.

The future studies include extending the questionnaire towards behaviour and attitudes to develop a comprehensive instrument that can foster long-term circularity. Expanding the sample to include additional countries and professional sectors would further enhance the applicability of the framework established in this study.

CRediT authorship contribution statement

Jeroen Dikken: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. **Rengin Aslanoğlu:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Visualization, Writing – original draft. **Qiuxian Li:** Validation, Writing – review & editing. **N. Cihan Kayaçetin:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Małgorzata Świąder:** Investigation, Writing – review & editing. **Grzegorz Chrobak:** Investigation, Writing – review & editing. **Aleksandra Lubańska:** Investigation, Writing – review & editing. **Jan K. Kazak:** Investigation, Supervision, Writing – review & editing. **Loredana Ivan:** Funding acquisition, Supervision, Writing – review & editing. **Gabriele Masera:** Funding acquisition, Supervision, Writing – review & editing. **Carlo Andrea Biraghi:** Investigation, Writing – review & editing. **Francesco Pittau:** Investigation, Writing – review & editing. **Evgenii Mateichik:** Investigation, Writing – review & editing. **Joost van Hoof:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Chiara Piccardo:** Funding acquisition, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research is a deliverable of the project Urban-CoLLaR: Co-creating Urban Living Labs for Circular Regenerative Neighbourhoods (F-DUT-2023-0138). This project was funded by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) (Project nr:224N048), Ministry of Enterprises and Made in Italy (MIMIT) (P/130001/01-02/X73), The Research Foundation - Flanders (FWO) (Project nr: S010323N), Taskforce for Applied Research (Regieorgaan SIA) (DUT.02.2), The National Centre for Research and Development (NCBR) (DUT/2023/4/Urban-CoLLaR/2025), and Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) (Contract no 121 from 20/02/2025), as part of Driving Urban Transitions (DUT) 2022-2025, Driving Urban Transitions 2023, co-funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 101069506.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clrc.2026.100468.

Data availability

Data will be made available on request.

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