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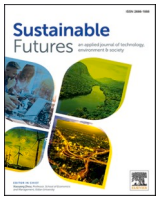

Investigating the effect of cognitive bias influences on sustainable decision-making in complex systems

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ABSTRACT

This study investigates the role of cognitive biases in decision-making within the Circular Economy and explores how these biases can be validated and addressed through empirical survey data. By developing a Conceptual Causal Loop Diagram and merging it with a foundational CLD, a comprehensive model was created to simulate the dynamics of CE systems. Key variables such as media influence, response to information, and behaviour change were incorporated into the Stock and Flow Diagram, enhancing the model's ability to represent real-world sustainability challenges. The principal results show that variations in biases and other factors can significantly impact CE outcomes, including individual actions, business priorities, and environmental responsibilities. The study highlights key variables, including media influence, response to information, behaviour change, and their roles in shaping CE outcomes. These components contextualize the study within the broader challenge of understanding and mitigating biases to foster sustainability, framing the research within the CE's ongoing efforts to achieve sustainable economic and environmental outcomes. Noteworthy conclusions include the identification of leverage points for promoting sustainability and the importance of understanding biases to improve decision-making processes in CE. The findings reveal biases saturate within approximately 100 months, while the perceived urgency for sustainability declines sharply within 50 months unless actively reinforced. This research contributes to the broader understanding of human factors influencing the transition to a sustainable economy.

1. Introduction

The imperative of sustainable production and consumption has become increasingly apparent in contemporary discourse, reflecting a global acknowledgement of the urgent need to mitigate environmental degradation, resource depletion, and social inequalities [1,2]. Sustainable development goals emphasize the intricate balance required to ensure economic prosperity, ecological integrity, and social equity for current and future generations [3,4]. The Circular Economy (CE) is central to this endeavour, a systemic approach that aims to minimize waste, promote resource efficiency, and foster closed-loop systems where materials and resources are continuously cycled [5,6].

Behavioral System Dynamics (BSD) offers a powerful approach to unravelling biases' complexities by combining behavioural science insights with system dynamics modelling [7]. This study seeks to explore how extensively BSD can uncover biases in the CE and assess their impact on sustainable production and consumption. Additionally, the research aims to validate these biases and their effects through empirical survey data, providing a robust foundation for analysis. By examining the extent to which biases shape perceptions and decisions, the study can identify areas for targeted interventions and offer actionable insights to promote more informed and sustainable choices across CE phases. Through this approach, the research contributes to a deeper understanding of the human factors driving or hindering progress toward a circular and sustainable future.

The research methodology includes validating a conceptual CLD and merging it with another Causal Loop Diagram (CLD) to provide a more comprehensive understanding of the relationships and interactions within the system. Then follows the integration of the new CLD data into an existing SFD.

At the heart of CE lies the challenge of decision-making within complex systems, where various stakeholders navigate intricate interdependencies. Within this context, understanding human behaviour and decision-making processes becomes paramount. BSD emerges as a promising methodology to unravel the complexities of human behaviour within dynamic systems [8]. By investigating the presence and impact of

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biases, this study aims to enhance our ability to design and implement effective strategies for sustainable resource management and consumption patterns.

Cognitive biases, deeply ingrained tendencies in human cognition, significantly influence decision-making processes [9]. From confirmation to status quo bias, these biases can lead individuals and organizations to make suboptimal choices, deviating from rational decision-making principles [10]. In the context of CE, where decisions impact resource utilization, waste generation, and environmental footprint, the potential consequences of cognitive biases are amplified. Failure to recognize and address these biases can undermine the efficacy of CE initiatives, hindering progress toward sustainable development goals [11].

Addressing biases in CE decision-making is imperative for several reasons. Firstly, biases can distort perceptions of risks and rewards, leading to misallocation of resources and missed opportunities for innovation [12]. Secondly, biases may perpetuate unsustainable consumption patterns, reinforcing linear, wasteful production models [13,14]. Thirdly, biases can impede stakeholders' adoption of CE practices, hindering the transition towards more circular and sustainable systems [15]. Therefore, elucidating and mitigating biases within CE decision-making processes are essential steps towards realizing the full potential of circularity in promoting sustainable development.

This study aims to achieve the following objectives: Identify cognitive biases that influence decision-making in the Circular Economy; Assess the impact of these biases on sustainable production and consumption; Validate the presence and effects of these biases using empirical survey data and develop strategies for mitigating the negative influence of biases in CE decision-making.

The hypotheses guiding this research include: H1: Cognitive biases significantly influence stakeholders' decision-making in the Circular Economy; H2: Addressing cognitive biases can enhance the adoption of sustainable production and consumption practices; H3: Media influence and public awareness mediate the relationship between biases and decision-making in the CE.

This study highlights the interplay between human behaviour, cognitive biases, and the Circular Economy. By leveraging the insights gathered from Behavioral System Dynamics and empirical survey data, this research aims to contribute to the development of evidence-based strategies for advancing sustainability within production and consumption systems.

2. Literature review

The literature on cognitive biases in sustainable production and consumption decision-making reveals a complex interplay between human behaviour, perceptions, and environmental considerations [16–18]. Existing research highlights a range of biases, such as status quo bias, anchoring bias, and confirmation bias, which can significantly shape individuals' attitudes toward sustainability and willingness to adopt Circular Economy (CE) practices [19–21]. These biases often lead to suboptimal decisions, favouring familiar or short-term benefits over long-term sustainability goals [22]. Despite the breadth of research on cognitive biases, there is a rareness of studies explicitly addressing their influence on CE phases, which involve resource circulation, waste reduction, and the integration of closed-loop systems [23–26]. The literature indicates a need for a more comprehensive analysis of cognitive biases within these phases, influencing stakeholders' decisions regarding production methods, consumption patterns, and resource management [27,28]. Such an understanding is crucial for devising strategies that mitigate biases and facilitate the transition toward more sustainable practices [29,30]. This study identifies thematic gaps in the literature to build upon these findings.

Theme 1: Biases in stakeholder decision-making: Research often examines biases in isolation without exploring their compounded effects across CE phases. Recent studies have begun to shed light on the various ways cognitive biases affect stakeholders across different sectors within the CE framework [31]. For instance, research has examined how biases can lead to the persistence of linear, wasteful production processes and hinder the adoption of innovative, sustainable alternatives [32]. Additionally, biases may affect consumers' choices, leading them to undervalue recycled or repurposed goods in favour of new products, even when the sustainable options offer comparable quality and benefits [33].

Stakeholders in the CE framework, including policymakers, industry leaders, and consumers, are subject to different biases that can shape their actions and preferences [34,35]. For instance, the endowment effect may lead to resistance toward changing existing practices, while myopic decision-making can result in a lack of long-term vision for sustainable development [36,37]. Understanding how these biases manifest across various stakeholder groups is critical to designing interventions that encourage the adoption of CE principles and promote a more sustainable economic model.

Despite the breadth of research on cognitive biases, few studies explicitly address their influence on CE phases, which involve resource circulation, waste reduction, and closed-loop integration. This study enhances the existing literature by outlining how specific biases influence various phases of the CE. Production phase: Status quo bias leads firms to resist adopting innovative sustainable materials. Consumption phase: Anchoring bias causes consumers to undervalue recycled or repurposed goods. Waste management phase: Confirmation bias reinforces existing wasteful disposal habits despite new recycling initiatives.

This targeted synthesis strengthens the argument for addressing biases at different levels of the CE framework.

Theme 2: Interaction dynamics: Limited work has analyzed how biases interact with external factors like media influence and policy environments to shape sustainability outcomes. The existing literature on cognitive biases in decision-making within sustainable production and consumption reveals several gaps the current research seeks to address [38,39]. Notably, there is a need for a more targeted examination of how specific biases influence decision-making across different phases of the Circular Economy. While some studies have addressed individual biases in isolation, a more holistic approach is required to understand the full scope of biases and their interactions within the CE framework [40,41]. Moreover, limited empirical research validates the impact of cognitive biases on stakeholders' behaviour within the CE, particularly across diverse industries and cultural contexts [42,43]. By leveraging empirical survey data, the current research aims to bridge this gap by providing robust evidence of how biases shape decision-making and affect adopting sustainable practices. Such insights are essential for developing effective strategies to mitigate biases and facilitate the transition toward a circular, sustainable economic model. Sustainable production and consumption encompass practices that minimize environmental impact and resource depletion while promoting social equity and economic viability [44,45]. This approach emphasizes efficient resource use, waste reduction, and the adoption of renewable materials throughout the lifecycle of products and services [46]. The Circular Economy framework extends these principles by advocating for closed-loop systems that recycle and repurpose materials, reducing reliance on finite resources and minimizing waste generation [47].

Theme 3: Empirical validation: While theoretical frameworks abound, empirical studies validating these frameworks in diverse cultural and industrial contexts remain scarce. In the Circular Economy, key stakeholders include policymakers, industry leaders, consumers, and civil society organizations [48]. Each group is critical in driving the transition toward sustainable production and consumption [49]. Policymakers can implement regulations and incentives to support CE practices, while industry leaders can adopt sustainable production methods and prioritize resource efficiency [50]. Consumers influence demand for sustainable products, and civil society organizations

advocate for environmental and social justice within CE phases [51].

The literature on cognitive biases affecting decision-making reveals how these biases can lead individuals and organizations to favour short-term gains or maintain the status quo over embracing long-term sustainable solutions [52]. For example, biases such as loss aversion, present bias, and information asymmetry may deter stakeholders from fully embracing CE practices [53]. Understanding these biases is crucial for identifying potential barriers to sustainable decision-making and developing targeted interventions to address them.

The thematic organization underscores the critical knowledge gaps and establishes a clear rationale for the methodologies employed in this study, enhancing the practical relevance of its findings. Cognitive biases in stakeholder decision-making: Existing studies often focus on biases in isolation, neglecting their compounded effects across various CE phases. This research offers a holistic perspective on these interactions by addressing this gap. Interaction dynamics between biases and external factors: Limited research investigates how cognitive biases intersect with factors such as media influence, policy environments, and socio-cultural contexts, which shape the sustainability landscape. Need for empirical validation: While theoretical insights dominate the field, empirical evidence substantiating these claims is sparse. This study bridges this gap by validating frameworks through data collected from diverse stakeholders.

The gaps in the literature described previously on cognitive biases and their impact on decision-making within the CE highlight the need for targeted research. There is a lack of empirical data on how biases operate across different stakeholder groups and cultural contexts and how they affect the adoption of CE principles. The current research aims to address these gaps by exploring the extent to which biases influence decision-making in the CE, using empirical survey data to validate findings and inform effective strategies for promoting sustainability.

3. Methods

The methods employed in this study combine conceptual modelling as defined by [54], empirical validation as described in [55], and a system dynamics analysis such as [56] to explore decision-making dynamics within the Circular Economy (CE). Central to the approach is developing a CLD grounded in existing research on cognitive biases, behavioural economics, and CE principles [57,58]. This model captures the relationships between cognitive biases, individual behaviour, and CE decision-making processes. The CLD serves as a foundation for the study, providing a visual representation of critical variables and feedback loops that influence decision-making within CE contexts.

To validate the Conceptual CLD, empirical survey data is collected from stakeholders across diverse sectors. This data offers real-world insights into perceptions, attitudes, and behaviours related to sustainability and CE practices. By comparing the model with survey responses, the research refines the CLD to align with observed behaviour and improve accuracy. The validated CLD is then merged with existing CLDs from prior studies, enriching the model's comprehensiveness. This refined model is subsequently used to modify existing System Dynamics Models (SDMs), enabling simulations of CE systems with updated data and insights. Through this iterative approach, the study aims to identify leverage points and potential interventions within the CE decision-making process, contributing to the broader goal of advancing sustainability.

The figure below outlines the methodology used in this study to understand and model decision-making processes in the CE through a combination of conceptual modelling and empirical validation.

The methods employed in this study combine conceptual modeling, empirical validation, and system dynamics analysis to explore decision-making dynamics within the Circular Economy as presented in Fig. 1. Developing a conceptual CLD: Identify and map cognitive biases and their relationships within the CE framework. Empirical data collection: Conduct surveys to collect data on stakeholders' perceptions, attitudes, and decision-making biases. Validate CLD with survey data: Align conceptual model with empirical findings to improve accuracy. Integration with existing CLD: Merge validated CLD with foundational models for a comprehensive view. System Dynamics simulation: Incorporate refined CLD into SDMs to explore leverage points and interventions.

The empirical survey data used for validation includes a sample size: 80 participants from industry, policy, and consumer groups. The demographics are diverse representation across age, gender, and sector. The survey instrument was structured questionnaire assessing perceptions, biases, and decision-making tendencies. The survey sample

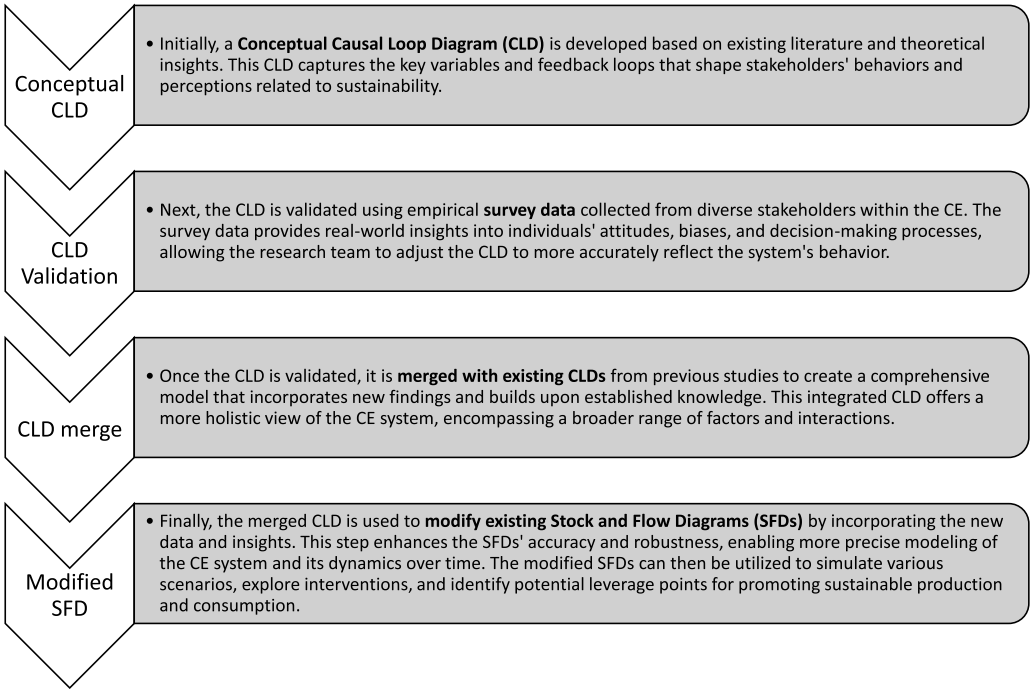

Fig. 1. Methodology process explained.

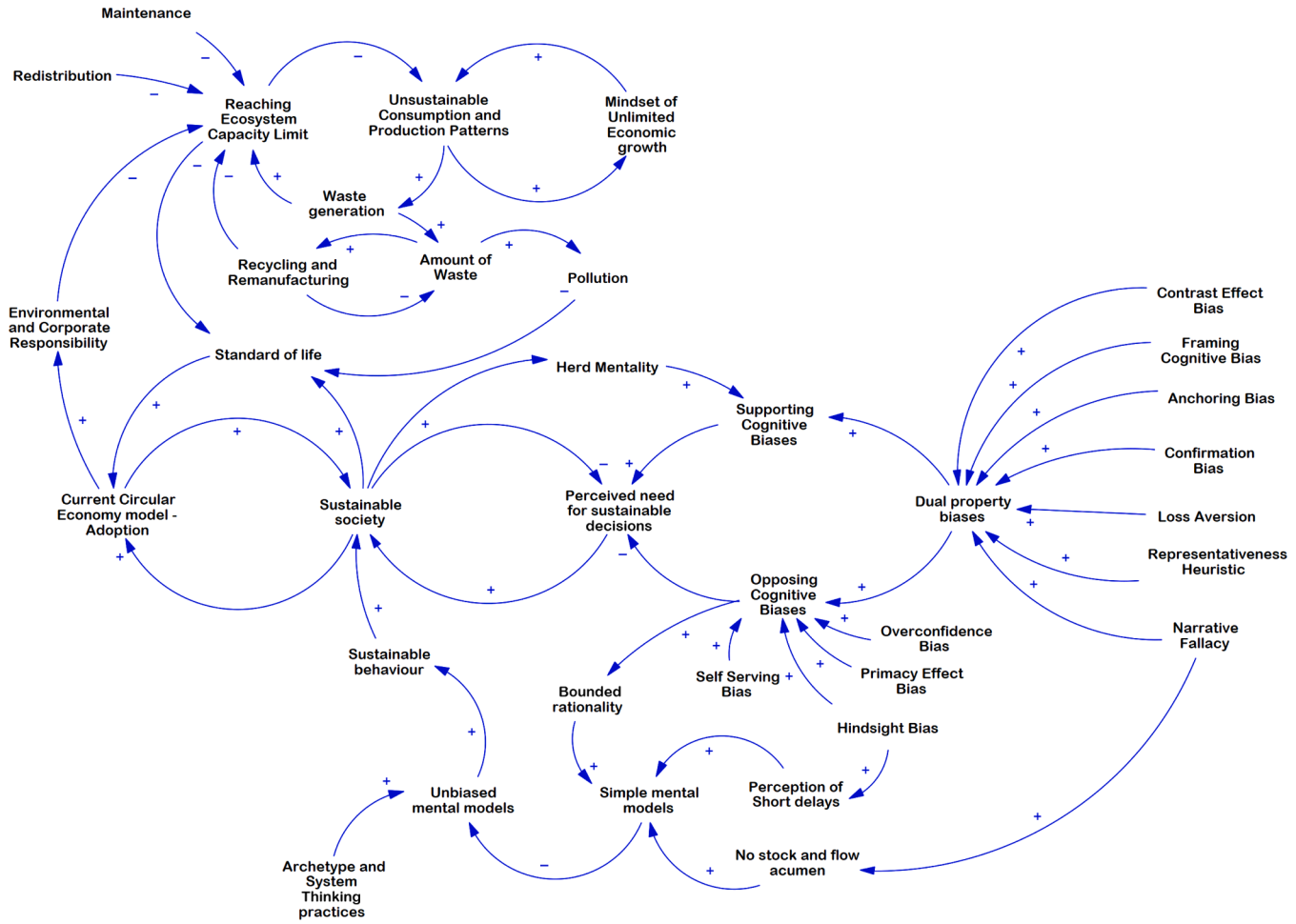

Fig. 2. Conceptual CLD, validated with survey data. B: Balancing loops. R: Reinforcing loops. +: Similar influence (positive to positive or negative to negative). -: Opposite influence (positive to negative or negative to positive). Blue arrows: direction of influence between variables.

represented a diverse cross-section of industries, with respondents most frequently employed in product manufacturing (over 70 %), followed by mining, farming, food production, and engineering services. Job titles ranged from senior engineers, reliability technologists, and operations managers to academic staff and students, indicating representation from both technical and managerial roles. While specific formal education data was not captured, the predominance of engineering and technical occupations suggests a high level of STEM-related qualifications. In terms of familiarity with CE practices, responses to items on recycling, repair, and re-use behaviours—both personally and professionally—showed that most participants actively engage in at least one CE-related practice. Common personal-life activities included recycling plastics, glass, and paper; repairing household items; and re-using containers or packaging. Professionally, CE practices were more constrained by industry regulations and organisational policies, though preventive maintenance, recycling of industrial materials, and equipment life extension were frequently reported. This industry and practice diversity supports the robustness of the empirical findings by indicating that the observed attitudes and biases towards sustainability and CE adoption are not restricted to a single sector or job function.

By capturing key variables and their interconnected relationships, the CLD provides a comprehensive understanding of the feedback loops that shape human behaviour and influence sustainable practices. Core variables within the CLD include cognitive biases, media influence, response to information, and behaviour change. The CLD elucidates several feedback loops, including reinforcing and balancing loops. Reinforcing loops highlight positive or negative reinforcement cycles, such as the impact of positive media influence on responses to information and subsequent sustainable behaviour. Balancing loops demonstrate regulatory mechanisms, such as the interplay between willingness to change habits, responses to information, and changes in sustainable behaviour. By examining these variables and their connections, the CLD provides insights into the potential leverage points and areas for intervention within the CE decision-making process. This in-depth analysis forms the basis for developing strategies to address biases and promote sustainable practices across different sectors.

The figure below presents the CLD that captures the CE system's complex relationships and feedback loops. This CLD visually represents key variables explained in the succeeding table and their interconnectedness and dynamic interactions. By mapping out these relationships, the CLD provides a comprehensive understanding of how different factors influence decision-making processes and sustainable practices within the CE framework. The diagram is a foundation for analyzing the system's behaviour and identifying potential interventions to promote sustainability across various CE phases. (Fig. 3, Fig. 4, Fig. 5)

Building upon this conceptual framework, the next phase of the methodology involves the validation of the conceptual CLD through empirical survey data collection. Using established survey instruments and methods drawn from prior research, stakeholders gather data from diverse sectors to capture perceptions, attitudes, and behaviours related to CE decision-making. This empirical validation process ensures the alignment of the conceptual CLD with real-world observations and experiences.

The table below provides an overview of key variables within the

	○ Agreement with fossil fuel reduction Gr=10	○ Agreement with sustainable practices Gr=21	○ Individual action Gr=23	○ Media influence Gr=48	○ Response to information Gr=37	○ Technology & innovation impact Gr=4
○ Negative Gr=26	3	9	7	18	14	2
○ Neutral Gr=16	3	3	6	10	7	2
○ Positive Gr=36	5	10	10	20	17	1

Fig. 3. Questions 6 and 10 - code co-occurrence table with grounded values.

	○ Better quality Gr=44	○ Green info accuracy Gr=21	○ Green info available Gr=33	○ Reduced cost Gr=52	○ Reusable Gr=53
○ SQ6 Gr=94	53	29	48	61	63

Fig. 4. Thematic analysis of question 6 with grounded values.

Fig. 5. Word cloud for all imported survey data to validate themes.

CLD, highlighting their definitions and significance in decision-making processes. By examining these variables, we gain insights into the complex interactions that drive or hinder sustainable practices and stakeholder behaviours within the CE context. (Table 1, Table 2, Table 3, Table 4)

This study conducts a qualitative analysis of survey data using Atlas.ti, a widely used qualitative data analysis software. Atlas.ti offers a comprehensive suite of tools for organizing, coding, and analyzing qualitative data, enabling researchers to derive rich insights from textual responses.

The analyzed survey research questions explore critical aspects of decision-making within the CE. These questions aim to uncover stakeholders' perceptions of sustainability, their willingness to change habits, and the factors influencing their decisions. By evaluating responses to these questions, the study seeks insights into how biases may impact CE practices and the potential areas for targeted intervention. The survey also assesses the impact of media influence and the perceived need for sustainability on behaviour change, offering a comprehensive view of

Table 1
Conceptual CLD variable discussion.

Variable	Discussion	Variable	Discussion
Media Influence (MI)	Media influence refers to the impact various media channels, including news outlets, social media, and advertisements, have on an individual's perception of sustainability and environmental issues. Positive media coverage can raise awareness and encourage individuals to adopt sustainable practices, while negative or misleading coverage can lead to scepticism and resistance [59].	Agreement with Sustainable Practices (ASP)	Agreement with sustainable practices indicates the degree to which individuals believe in and support actions and behaviours that promote sustainability. This variable reflects how much a person aligns with principles such as recycling, conservation, and responsible consumption [60].
Response to Information (RI)	Response to information measures how individuals react to new information or media that challenges their views on sustainability and the environment. Positive responses might include a willingness to adapt and change behaviours, while negative responses may lead to scepticism or resistance [61].	Agreement with Fossil Fuel Reduction (FFR)	Agreement with fossil fuel reduction represents an individual's stance on the need to decrease the use of fossil fuels in favour of cleaner, sustainable energy sources. A higher level of agreement suggests a preference for renewable energy and efforts to reduce carbon emissions [62].
Behaviour Change (BC)	Behaviour change refers to adopting new practices or habits that align with sustainability goals. This can include consumption patterns, waste management, and energy usage changes. Positive behaviour change is essential for achieving sustainability targets at an individual and societal level [63].	Agreement with Public Awareness (PA)	Agreement with public awareness measures how much individuals believe in raising awareness about environmental issues and sustainability. The high agreement suggests support for education and outreach efforts to inform the public and drive change [64].
Willingness to Change Habits (WH)	Willingness to change habits assesses an individual's openness to modifying their lifestyle and consumption patterns to support sustainability and environmental protection. A strong desire indicates a readiness to embrace new practices aligned with sustainable living [65].	Individual Action (IA)	Individual action evaluates the extent to which a person takes personal initiative to support sustainability efforts. This includes reducing waste, conserving resources, and advocating for environmental causes [66].
Cognitive Bias Impact (CBI)	Cognitive bias impact examines how an individual's biases, such as confirmation bias or status quo bias, affect their perception of and engagement with sustainability practices. The high impact of cognitive biases can hinder the adoption of sustainable behaviours [67].	Technology and Innovation Impact (TI)	Technology and innovation impact assesses the belief in the potential of new technologies and innovative solutions to address environmental challenges. A high perceived impact suggests confidence in the role of technology in promoting sustainability [68].
Business Sustainability Priority (BSP)	Business sustainability priority evaluates how much individuals believe businesses should prioritize sustainability in their decision-making processes. This includes ethical sourcing, waste reduction, and sustainable product design considerations [69].	Belief in Human-Caused Climate Change (CC)	Belief in human-caused climate change measures the extent to which individuals attribute climate change to human activities such as greenhouse gas emissions. A strong belief in this connection often motivates individuals to support policies and practices to mitigate climate change [70].
Cognitive Bias Influence (CBI2)	Cognitive bias influences how an individual's biases shape their approach to change and innovation within the Circular Economy. This includes resistance to adopting new practices due to entrenched habits or scepticism towards new information. While both variables deal with the influence of cognitive biases, CBI1 focuses on the impact of biases on decision-making and sustainable practices. At the same time, CBI2 examines how biases contribute to resistance to change and the adoption of circular economy practices [71].	Resistance to Change (RC)	Resistance to change evaluates the degree to which individuals oppose or hesitate to change their habits or adopt new practices. High resistance may stem from cognitive biases, lack of information, or entrenched norms, posing challenges to sustainability initiatives [72].

the decision-making landscape in CE contexts.

Through this analysis, the research aims to contribute to a better understanding of the human factors driving or hindering sustainable development. The following table shows the questions evaluated in this study:

The qualitative analysis process commenced with transcribing and importing survey responses into the Atlas.ti platform. Responses were then systematically coded using deductive and inductive coding techniques. Deductive coding involves the application of pre-defined codes derived from the conceptual framework and research literature. In contrast, inductive coding allows for the emergence of new themes and categories from the data.

Once coded, the data was organized into thematic networks and matrices within Atlas.ti, facilitating the exploration of relationships between codes and themes. Through constant comparison and iterative

Table 2
Survey questions and discussions.

Question number in the survey	Question	Discussion
Question 6:	"Which of the following factors will convince you to buy/use sustainable products?"	This question explores the decision-making factors related to sustainability, providing insights into what influences individuals in choosing sustainable options.
Question 7:	"Are you willing to change your habits to be more sustainable?"	This question directly addresses the willingness of individuals to change their behaviours for the sake of sustainability, shedding light on their openness to adopting circular economy practices.
Question 10:	"How do you respond to information or media that challenges your views on sustainability and the environment?"	Understanding individuals' responses to challenging information about sustainability can help reveal potential cognitive biases in their perceptions and decision-making processes.
Question 12:	"How much do you believe that cognitive biases can impact the success or failure of circular economy initiatives?"	This question directly addresses the perceived influence of cognitive biases on circular economy initiatives, providing valuable insights into participants' awareness of cognitive biases in this context.
Question 14 (multiple statements):	"To what extent do you believe cognitive biases influence decision-making in adopting circular economy principles and practices?" "To what extent do you think that cognitive biases play a role in the resistance to change and adoption of circular economy practices?"	Several statements within Question 14 are relevant to understanding individuals' beliefs and attitudes toward sustainability, environmental practices' importance, and cognitive biases' role in decision-making.

refinement, patterns and trends within the data were identified, providing deeper insights into stakeholder perceptions, attitudes, and behaviours related to Circular Economy decision-making.

Atlas.ti's powerful query and visualization tools were instrumental in conducting deeper qualitative data analyses. Queries were run to explore connections between codes, examine differences across respondent groups, and identify outliers or contradictory responses. Visualizations such as word clouds, frequency plots, and co-occurrence networks were utilized to enhance data interpretation and presentation.

Throughout the qualitative analysis process, rigorous attention was paid to ensuring the trustworthiness and reliability of the findings. Techniques such as member checking, peer debriefing, and inter-coder reliability checks were employed to enhance the validity and credibility of the analysis.

These selected questions provide a foundation for gathering data on cognitive biases and decision-making in adopting CE principles. The responses to these questions contribute to the results and discussion sections of the paper, helping to explore the impact of biases on sustainability practices. The following table discusses the validation of the variable connection.

The feedback loops are discussed in the following table. Notably, the entire CLD is only balanced by one loop and reinforced by five loops.

This CLD captures the dynamic relationships between media influence, responses to information, willingness to change habits, cognitive biases, and various attitudes toward sustainability. The reinforcing and balancing loops illustrate the complexities and interdependencies within the system. Analyzing these loops can provide insights into leverage points for interventions and a deeper understanding of the factors

Table 3
Variables connection and discussions.

Variable connection	Connection discussion	Proven by survey or literature
MI to RI	Positive media influence may lead to a positive response to information. Negative media influence may lead to an adverse reaction to information.	Survey data: Grounded frequency of MI=48 Grounded frequency of RI=37 Co-occurrence = 26
RI to BC	Positive and open responses to information may lead to increased sustainable behaviour. Adverse reactions to information may lead to decreased sustainable behaviour.	Survey data: Grounded frequency of BC = 30 Co-occurrence = 13 Positive Co-occurrence = 32 Neutral Co-occurrence = 14 Negative Co-occurrence = 22
BC to MI	Describes how increased sustainable behaviour can lead to more positive or supportive media coverage of sustainability issues.	Survey data: Co-occurrence = 14 Positive Co-occurence = 35 Neutral Co-occurence = 17 Negative Co-occurence = 26 [73–75]
MI to WH	Indicates how increased media coverage and information about sustainability can lead to a higher willingness to change habits to align with sustainable practices.	
WH to BC	A high willingness to change habits may lead to increased sustainable behaviour. A low desire to change habits may lead to no change or decreased sustainable behaviour.	Survey data: Question 7, 78 answered Yes, and one answered No.
MI to CBI	Suggests that increased media influence can mitigate the impact of cognitive biases on decision-making, leading to more rational and informed choices.	[9,76,77]
CBI to BC	A high perceived impact of cognitive biases may lead to decreased sustainable behaviour.	Survey data: Question 12, 33 answered Very likely, 30 answered Somewhat likely, 11 answered Neither likely nor unlikely, four answered Somewhat unlikely, and one responded Very unlikely.
MI to CC	Increasing media influence on climate change topics can strengthen individuals' belief in human-caused climate change.	Survey data: Grounded frequency of CC = 31 Co-occurrence = 10 Positive Co-occurrence = 35 Neutral Co-occurrence = 16 Negative Co-occurrence = 30
CC to ASP	Shows how a strong belief in human-caused climate change can lead to a more remarkable agreement with and support for sustainable practices.	[70,78]
ASP to BC	Agreement with sustainable practices may positively influence behaviour change.	[79,80]
BC to CBI2	Suggests that increased sustainable behaviour can decrease cognitive biases influencing decision-making and resistance to change.	Survey data: Question 14.1, 2 answered Strongly disagree, 1 answered Disagree, nine answered Neither agree nor disagree, 45 answered Agree, and 22 responded Strongly agree.
CBI2 to RC	The high perceived influence of cognitive biases may contribute to resistance to change.	Survey data: Question 14.2, 2 answered Strongly disagree, 2 answered Disagree, four answered Neither agree nor disagree, 44 answered Agree, and 27 responded Strongly agree.
RC to BC	Illustrates how increased resistance to change can lead to decreased sustainable behaviour.	[81–83]

(*continued on next page*)

Table 3 (*continued*)

Variable connection	Connection discussion	Proven by survey or literature
BC to IA	More sustainable behaviour may positively influence higher individual action.	Survey data: Grounded frequency of IA = 23 Co-occurrence = 14 Positive Co-occurrence = 25 Neutral Co-occurrence = 13 Negative Co-occurrence = 15
IA to PA	Demonstrates how increased individual action can raise public awareness of sustainability issues.	[84,85]
PA to BC	Agreement with the importance of public awareness may positively influence behaviour change.	[86,87]
IA to TI	Shows how increased individual action can contribute to the impact of technology and innovation on sustainability.	Survey data: Grounded frequency of TI = 4 Co-occurrence = 1 Positive Co-occurrence = 11 Neutral Co-occurrence = 8 Negative Co-occurrence = 9
TI to BSP	Indicates how a higher impact of technology and innovation can lead to more excellent business prioritization of sustainability.	[88,89]
BSP to FFR	Increasing business emphasis on sustainability can lead to more significant efforts to reduce fossil fuel usage.	[90–92]
FFR to BC	Agreement with fossil fuel reduction may positively influence sustainable behaviour.	Survey data: Grounded frequency of FFR = 10 Co-occurrence = 3 Positive Co-occurrence = 20 Neutral Co-occurrence = 10 Negative Co-occurrence = 11

influencing sustainable behaviour.

Subsequently, the validated conceptual CLD is integrated with existing CLDs derived from systems analysis and modelling approaches. By merging conceptual insights with empirical evidence, this synthesis enriches the robustness and comprehensiveness of the overall CLD, capturing the nuances and complexities inherent in CE decision-making dynamics.

Finally, the modified CLD is incorporated into existing System Dynamics Models (SDMs), enabling the integration of new empirical data and insights into dynamic simulations of CE systems. Through iterative model refinement and validation cycles, the SDMs are calibrated to reflect the updated understanding of cognitive biases and their implications for CE decision-making.

The integration process involves identifying standard variables and feedback loops in both models. The established connections and relationships between the two CLDs were examined between these shared elements. This process required adjustments to align the relationships between variables. Once the common elements have been identified and aligned, we incorporated additional variables and feedback loops from the current CLD into the existing CLD. This step expanded the existing model's scope to include the new variables and their relationships, providing a more complete and nuanced understanding of the CE system. The merged CLD was reviewed to ensure consistency, coherence, and robustness. Any redundancies or discrepancies between the models were addressed through iterative refinements. By reconciling differences and fine-tuning the merged CLD, we ensured the model accurately represents the complex decision-making dynamics within the CE.

Finally, the merged CLD was validated again using expert feedback to confirm its accuracy and practical applicability. This comprehensive model is a valuable tool for exploring potential interventions and leverage points within the CE system, contributing to more effective strategies for promoting sustainability.

The following figures show the foundational CLD, and the subsequent figure shows the merged diagram.

Table 4
Feedback loops and discussions.

Feedback Loops	Discussion	Feedback Loops	Discussion
Reinforcing Loop (R1)	High MI → Positive RI → Increased BC → High MI (a cycle of positive reinforcement) Low MI → Negative RI → Decreased BC → Low MI (a cycle of negative reinforcement)	Reinforcing Loop (R2)	High WH → Increased BC → Positive MI → High WH (a loop reinforcing positive responses and increased sustainable behaviour) Low WH → No/ Decreased BC → Negative MI → Low WH (a loop reinforcing less willingness, negative responses, and decreased sustainable behaviour)
Reinforcing Loop (R3)	High MI → Strong Belief in Human-Caused Climate Change (CC) → Strong Agreement with Sustainable Practices (ASP) → Increased Behavior Change (BC) → High MI (a cycle of positive reinforcement)	Reinforcing Loop (R4)	Increased Behavior Change (BC) → High Individual Action (IA) → Strong Agreement with Public Awareness (PA) → Increased Behavior Change (BC) (a cycle of positive reinforcement)
Reinforcing Loop (R5)	Increased Behavior Change (BC) → High Individual Action (IA) → High Technology and Innovation Impact (TI) → Strong Business Sustainability Priority (BSP) → Strong Agreement with Fossil Fuel Reduction (FFR) → Increased Behavior Change (BC) (a cycle of positive reinforcement)	Balancing Loop (B1)	Increased Behavior Change (BC) → Decreased Cognitive Bias Influence (CBI2) → Decreased Resistance to Change (RC) → Increased Behavior Change (BC) (a cycle of balancing reinforcement)
Balancing Loop (B2)	Increased Media Influence (MI) → Decreased Cognitive Bias Impact (CBI) → Increased Behavior Change (BC) → Increased Media Influence (MI) (a cycle of balancing reinforcement)		

The common elements between the conceptual CLD and the foundational CLD are marked in different colours to show the merging connections.

In the merged CLD, the connections between common elements from the conceptual CLD and the foundational CLD are highlighted using distinct colours to illustrate the merging connections. These connections reveal the intricate relationships within the system and offer insights into how different variables interact to shape sustainability outcomes. Let's expand on each connection with explanations and examples:

Business sustainability is prioritized positively with the environment and corporate responsibility through other variables. This connection shows that a higher priority given to business sustainability can lead to positive outcomes for the environment and an increased sense of corporate responsibility. When businesses prioritize sustainability, they adopt reducing waste, conserving resources, and investing in renewable energy. For example, a company that sets ambitious sustainability goals may implement recycling programs, switch to green energy sources, and design products focusing on longevity and recyclability. These

initiatives contribute to environmental protection and reflect a sense of corporate responsibility towards the community and the planet.

Individual actions are negatively connected with unsustainable production and consumption patterns. This connection highlights that individual actions taken towards sustainability can help reduce unsustainable production and consumption patterns. When individuals make conscious choices to reduce their environmental footprint, it can lead to changes in demand and practices throughout the supply chain. Individuals who use reusable bags, avoid single-use plastics, and support companies with ethical and sustainable practices influence market demand. This shift in consumer behaviour encourages businesses to adopt more sustainable production methods and offers alternatives to unsustainable products.

Supportive cognitive biases negatively affect the influence of cognitive biases. Supportive cognitive biases, such as confirmation bias towards sustainable practices, can negatively influence cognitive biases that may otherwise resist change. This dynamic suggests that supportive biases may counteract or diminish the impact of opposing biases. An individual who supports recycling may ignore information that downplays its importance, thus allowing their supportive bias to guide their decisions rather than being swayed by conflicting data.

The opposing cognitive biases positively connect with the influence of cognitive biases. This connection suggests that opposing cognitive biases, such as scepticism towards sustainability initiatives, can reinforce other cognitive biases, amplifying their impact on decision-making. This dynamic may result in resistance to change and slow the adoption of sustainable practices. A business leader sceptical of climate change may be more inclined to downplay environmental concerns and prioritize short-term gains, reinforcing their cognitive biases and influencing the company's policies against adopting sustainable practices.

The integration of the conceptual CLD with the foundational CLD is a critical aspect of this study. A clear narrative is provided to explain the merging process: Selection of common variables: Identified overlapping variables in both CLDs; Incorporation of new elements: Introduced missing feedback loops to refine the model and validation of merged CLD: Conducted expert review to ensure logical coherence. These connections within the merged CLD reveal the complex interplay between cognitive biases, business priorities, and individual actions in shaping sustainability outcomes. By understanding these relationships, stakeholders can identify leverage points and develop strategies to promote more sustainable behaviours and practices across various sectors. The CLD maps relationships between environmental responsibility, unsustainable consumption patterns, business priorities, and individual actions, linking them through reinforcing (R) and balancing (B) feedback loops. Variables such as Supporting and Opposing Cognitive Biases, Media Influence, and Behaviour Change connect perception, decision-making, and societal outcomes. Positive (+) arrows indicate direct relationships, while negative (–) arrows represent inverse effects. The diagram highlights leverage points—like Media Influence and Perceived Need for Sustainable Decisions—where interventions could shift behaviours towards sustainable practices.

The last step of the process is to merge the new CLD into the existing SFD from the foundational CLD. This step involves the conceptual CLD variables.

In an SFD, variables are organized into stocks and flows to represent the structure and dynamics of a system over time. Stocks are

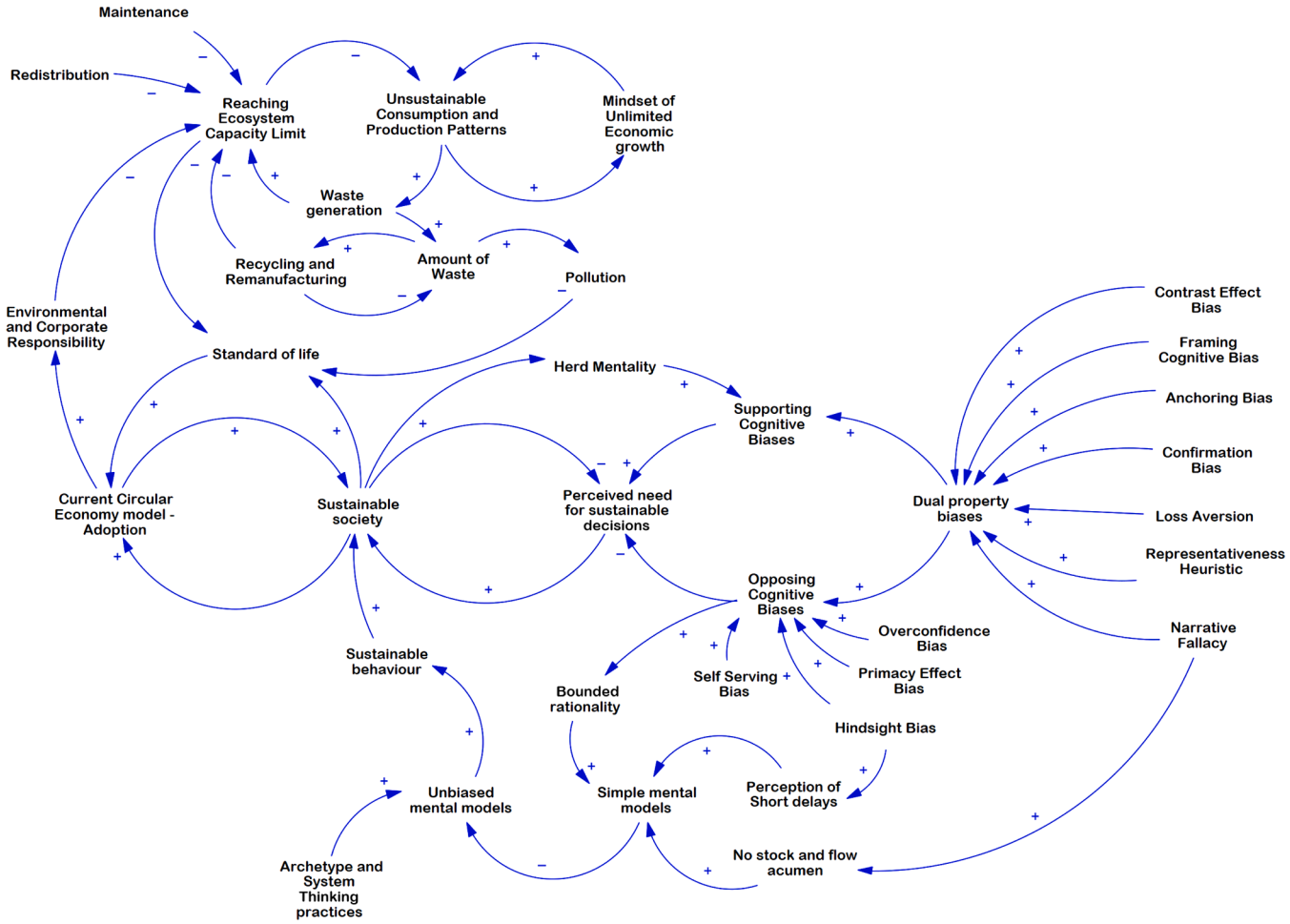

Fig. 6. Foundational CLD from [93]. Blue arrows: Direction of influence. +: Similar influence polarity.-: Opposite influence polarity.

accumulations of quantities within a system, such as resources or conditions, while flows represent the rates at which quantities move into or out of stocks. By modelling the system's stocks and flows, we can simulate the behaviour and interactions of different variables over time. The CLD fromFig. 7 was used in a previous study to model the following SFD. The simulations are explained in the next section.

The diagram indicates that the inflow into the biases stock originates from the mental models individuals hold in society. The initial value of the stock is set at 201, based on the coded data and representing the sum of all initial opposing biases. The initial value for the Opposed Cognitive Biases variable is similarly determined from the coded data, serving as the simulation's capacity. This initial value is calculated to be 1015, representing the total biases present in the survey.

The first variable, the perceived need for sustainability, is described in equation (1):

Need for Sustainability=Reference Sustainability Rate× Effect of Biases on Perceived Need for Sustainability _____(1)

The reference sustainability need rate is derived from three survey questions concerning focus and informed sustainability awareness, with a calculated value of 0.134. The reference supporting cognitive biases are derived from the ratio of the total bias count from 14 survey questions and the total supportive bias count from the same dataset, resulting in a value of 0.80. This provides a basis for the crucial relationship between biases and their impact on the perceived need for sustainability, as expressed in equation (2):

Effect Of Biases On The Perceived Need For Sustainability = Supportive Cognitive Biases /Reference Supporting Cognitive Biases_____(2)

When biases align accurately with opposing cognitive bias influences, supporting biases are entirely diminished, as illustrated in equation (3):

Supportive Cognitive Biases =1 - (Biases / Opposed Cognitive Biases) _____(3)

The powerful features of the Vensim software were used to simulate the system's behaviour over time, greatly enhancing the model's reliability in representing real-world decision-making processes. The simulations utilized a step increment of 0.25, starting from an initial value of 0.00 to a final value of 100.0. These parameters are vital in shedding light on the model's dynamic evolution.

A CLD can modify an existing SFD by providing additional insights into the feedback loops and interdependencies within the system [93, 94]. The CLD in Fig. 7 captures the cause-and-effect relationships between variables and highlights the dynamic interactions that drive system behaviour.

By examining the newly combined CLD, we identified areas where new variables, connections, or feedback loops can be integrated into the existing SFD, as shown in Fig. 8. This process adds more detail to the SFD, enhancing its ability to model complex system dynamics accurately. Incorporating insights from the CLD also helped to reveal potential leverage points, critical pathways, and areas of non-linearity within the system, leading to a more comprehensive and nuanced understanding of the system's behaviour over time. The survey data served

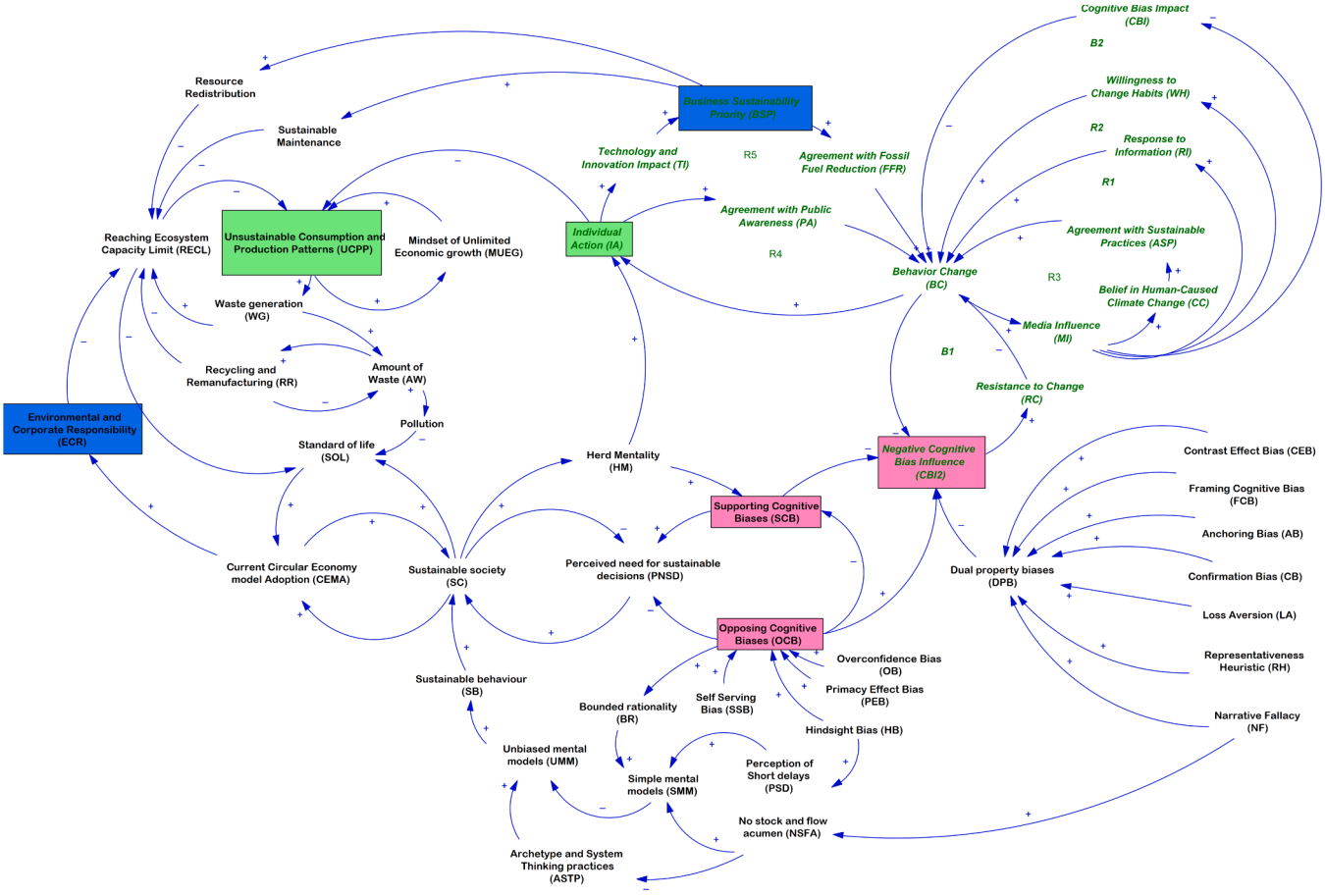

Fig. 7. New CLD combined from Fig. 2 and Fig. 6.
Blue variables: From Foundational CLD in Fig. 6. Organisational or policy-level drivers (e.g., Environmental and Corporate Responsibility, Business Sustainability Priority). Green variables: New variables identified. Individual or societal actions and perceptions (e.g., Individual Action, Perceived Need for Sustainable Decisions). Pink variables: Overlapping variable. Cognitive bias categories and influences (e.g., Supporting Cognitive Biases, Opposing Cognitive Biases). "+" sign: Positive causal relationship — an increase in the source variable causes an increase in the target variable (or a decrease causes a decrease). "–" sign: Negative causal relationship — an increase in the source variable causes a decrease in the target variable (or vice versa).

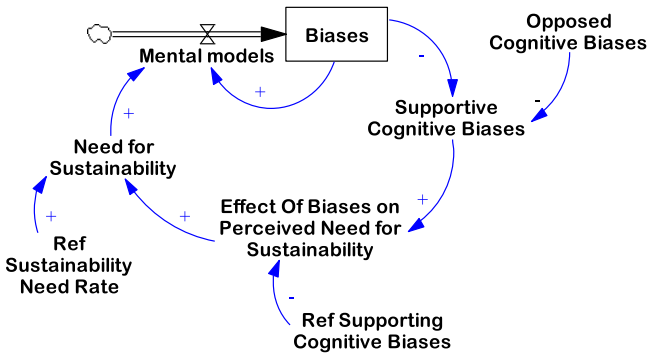

Fig. 8. Stock and flow diagram foundation from [93]. Blocked variable: Stock. Blue arrows: Directionality of influence.

as the basis for establishing initial values and parameters in the SFD, allowing for a more precise representation of the interactions between different variables. For example, the initial values for stocks, such as biases and media influence, were set based on the frequency and intensity of responses coded in the survey data. Similarly, the inflow and outflow rates for variables such as response to information and behaviour change were calibrated according to the patterns and trends observed in the survey data.

The survey answers were incorporated into the SFD by translating grounded frequencies from qualitative data into quantitative values. Using Atlas.ti, the survey responses were coded and categorized into positive, neutral, and negative frequencies, reflecting participants' attitudes and perceptions regarding sustainability and biases.

These frequencies were then used to assign quantitative values to critical variables in the model, such as media influence, response to information, and behaviour change. Positive frequencies indicated a favourable stance toward sustainability, neutral frequencies represented ambivalence, and negative frequencies suggested resistance or scepticism. The SFD could accurately reflect stakeholder attitudes and biases by converting these qualitative insights into numerical data, providing a more precise and nuanced representation of the system's dynamics. This approach enabled the model to account for participant response variations, enhancing the simulations' reliability and the subsequent analysis.

In the provided scenario, we have two stocks:

The other variables in the model are:

The new SFD in the following figure presents an enhanced representation of the circular economy system, incorporating key variables such as Media Influence, Response to Information, and Behavior Change. The updated SFD allows for a comprehensive analysis of how these variables impact the system's behaviour, offering insights into practical strategies for advancing sustainability. This stock-and-flow diagram integrates the validated CLD (Fig. 7) into a system dynamics structure, showing the accumulation and depletion of key stocks over time. Stocks are represented by rectangular nodes, flows by double-lined arrows, and converters by circle lines. Feedback structures are annotated directly within the figure, and variable names are cross-referenced in Table 6 for clarity. (Fig. 9)

In the new SFD, the inflow of the biases stock is influenced by the mental models individuals hold within society and the influence of media. These mental models are not isolated constructs but intricate outcomes shaped by three key factors. Perceived Need for Sustainability, which is the extent to which individuals perceive the importance of sustainability, dramatically influences their mental model and serves as a fundamental building block. Both supportive and opposing biases

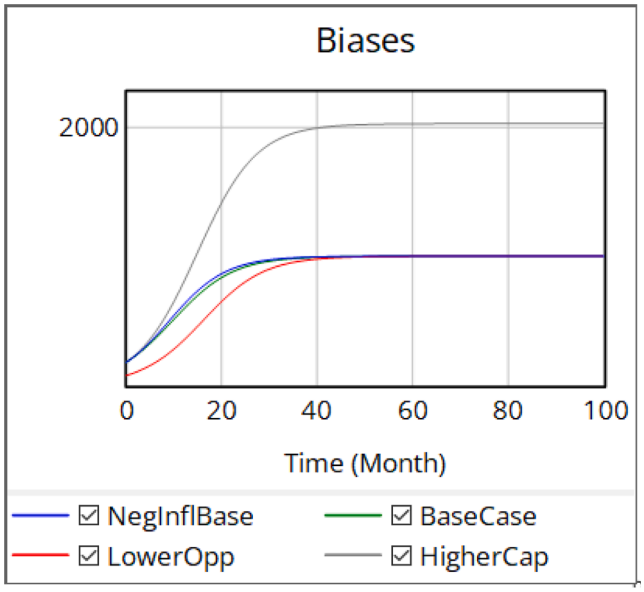

Fig. 10. Biases simulation graph.

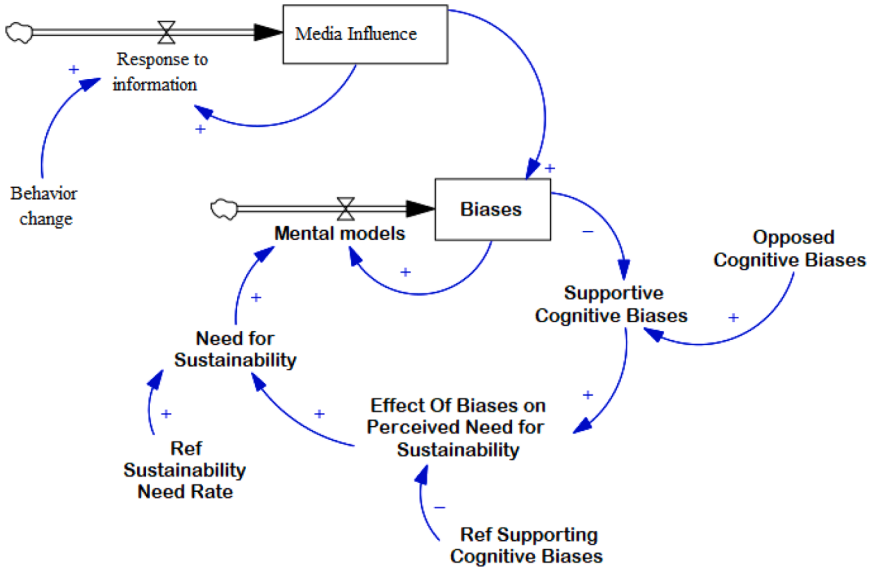

Fig. 9. New combined SFD.

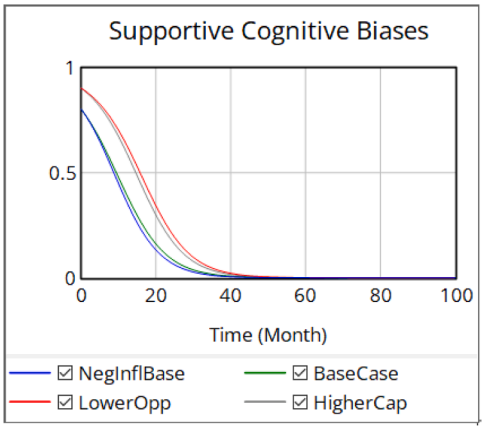

Fig. 11. Supportive cognitive biases simulation graph.

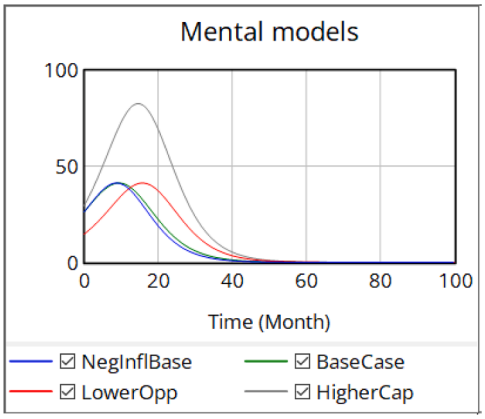

Fig. 12. Mental models simulation graph.

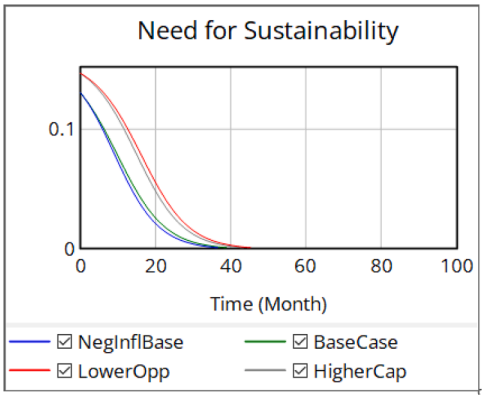

Fig. 13. Need for sustainability simulation graph.

substantially shape these mental models. The quantity and nature of these biases play a significant role in influencing an individual's perspective. The media's impact on sustainability topics can shape mental models by affecting perceptions and biases, serving as a powerful external force.

Incorporating new variables such as Response to Information (RI) and Behavior Change (BC) was essential for expanding the model and representing the influence of individual behaviour and new information on the biases stock. RI is an inflow to the Media Influence stock, indicating how individuals react to new information about sustainability and biases. Similarly, BC is an inflow to the RI variable, reflecting how

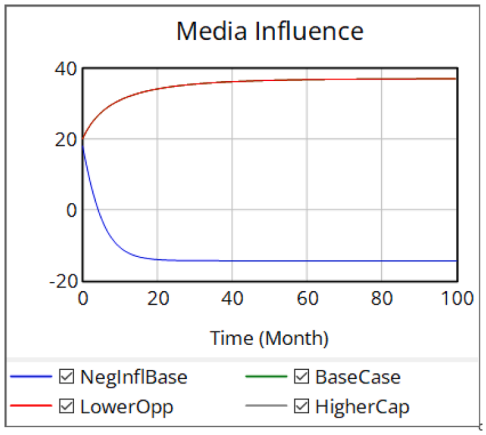

Fig. 14. Media influence simulation graph.

individuals' adoption of new behaviours can influence responses over time.

Adjusting the equations and parameters to include these new variables helped to capture the intricate interplay between biases, media influence, behaviour change, and perceived need for sustainability, further refining the system's dynamics and insights into sustainable decision-making. The changes in equations and new equations are discussed in Tables 5 and 6.

4. Results and discussion

To model the system and simulate its behaviour over time, various calculations and approaches were employed:

Using these modelling techniques, the SFD diagram simulated the dynamic interactions between biases, media influence, supportive and opposing biases, the perceived need for sustainability, response to information, and behaviour change. This simulation helps to explore the system's behaviour under different scenarios and inform effective strategies for promoting sustainable practices. The following figures depict the outcomes of the sensitivity analysis simulations, offering insights into how variations in key parameters affect the model's behaviour. This analysis allows us to understand the impact of changes in initial values, capacities, and rates on system dynamics. By exploring different scenarios, we can evaluate how shifts in opposing biases, perceived need for

Table 5
Stock and flow diagram - stock discussions.

Stock	Discussion	Initial conditions and sensitivity analysis conditions (SAC)
Stock 1: Biases	This stock represents the accumulation of cognitive biases within the system. Cognitive biases can impact individuals' perceptions, decision-making, and behaviour related to sustainability.	Initial value from [93] =201 SAC: LowerOpp case = 100
Stock 2: Media Influence	This stock represents the impact of media on individuals' perceptions and attitudes towards sustainability. Positive or negative media coverage can influence how individuals perceive sustainability issues. Survey frequencies from thematic analysis: Grounded frequency = 48 Positive = 20 Neutral = 10 Negative = 18	Initial value = 20 SAC: BaseCase, LowerOpp, HigherCap = Response to information*(1-Media Influence/48) SAC: NegInfl = (Response to information)*(1-Media Influence/48)-18*(18/48)

Table 6
Stock and flow diagram - variables discussions.

Variable	Discussion	Initial conditions, rate of flow, and sensitivity analysis conditions (SAC)
Supportive Biases and Opposing Biases	These variables influence the accumulation of biases (Stock 1). Supportive biases encourage individuals to support sustainable practices, while opposing biases discourage them.	Ref Supportive=0.80 [93] Equation 3, as described above Opposing Cognitive biases =1015 (capacity) SAC: HigerCap = Opposing Cognitive biases =2030 (capacity)
Effect of Biases on Perceived Need for Sustainability	This variable captures how biases impact individuals' perceived need for sustainability. It influences the degree to which people recognize and prioritize sustainable practices.	Equation 2, as described above
Need for Sustainability	This variable represents the actual need for sustainable practices within the system. The effect of biases on the perceived need for sustainability influences it.	Reference Sustainability Need Rate = 0.134 [93] Equation 1, as described above
Mental models	The mental model variable is a critical component of the SFD flow model, as it influences how individuals perceive and engage with sustainability issues. By understanding the interplay between mental models, biases, and other variables, stakeholders can design more effective strategies to promote sustainable practices and advance the Circular Economy.	=Biases x Need for Sustainability
Response to Information	This variable represents how individuals react to new information about sustainability. Positive responses can lead to changes in behaviour, while negative responses may reinforce existing biases. Survey frequencies from thematic analysis: Grounded frequency = 37 Positive = 17 Neutral = 7 Negative = 14	SAC: BaseCase, LowerOpp, HigherCap =17*Behavior change*(1-Media Influence/37) SAC: NegInfl = 14*Behavior change*(1-Media Influence/37)
Behavior Change	This variable represents changes in individual behaviours towards more sustainable practices. It can be influenced by the response to information and the perceived need for sustainability. Survey frequencies from thematic analysis: Grounded frequency = 30 Positive = 15 Neutral = 7 Negative = 8	SAC: BaseCase, LowerOpp, HigherCap =15/30 SAC: NegInfl =8/30

sustainability, and other critical factors influence outcomes within the circular economy model. These simulations provide valuable information for identifying leverage points and areas where targeted interventions could enhance sustainability practices and decision-making processes.

In the graphs, the horizontal axis is labelled "Time [months]," and the vertical axis uniformly uses units of measurement such as [number/ratio of]. Months provide a suitable level of granularity for capturing system dynamics without becoming too detailed or overwhelming. It allows for meaningful insights while maintaining a manageable scope. Months offer a realistic time frame for observing changes within the system. Decision-making processes and behavioural shifts often unfold over weeks or months rather than days, making months an appropriate unit of measurement. The model serves as an initial exploration of the system, focusing on establishing baseline relationships and dynamics. Subsequent iterations or refinements could include time delays for a more nuanced analysis.

The Biases simulation graph demonstrates an upward S-shaped growth, indicating how biases evolve under different scenarios. The base case shows biases growing to a median level within a specific period, reflecting a typical S-shaped growth pattern. This is consistent with logistic growth, where biases increase rapidly initially and then level off as the system approaches its carrying capacity. The LowerOpp scenario exhibits a lower S-shape and reaches the median later than the base case, indicating that lower opposing biases result in slower growth. This suggests that the lack of opposition allows biases to take longer to reach their full potential, affecting the growth rate.

The HigherCap scenario demonstrates biases reaching their maximum simultaneously as the base case but reaching a higher level overall due to the increased capacity for biases. This behaviour implies that the system can accommodate more biases, allowing for a more pronounced growth without a significant change in the timing of peak biases. Finally, the NegInflBase scenario, which includes the negative influence of behaviour changes and response to information, shows biases above the base case. This suggests that these negative influences slightly enhance the growth of biases, perhaps by reinforcing certain biases or diminishing opposing forces. Overall, these scenarios illustrate how changes in capacity, opposing biases, and negative influences can impact the growth pattern of biases within the system. By examining these different cases, one can better understand the factors that shape the evolution of biases and how they may be managed to support sustainable practices. The simulation progresses over 0 to 100 months, allowing observation of how biases change dynamically within this period.

The Supportive Cognitive Biases simulation graph illustrates a downward S-shaped growth, showing how supportive biases decrease over time across different scenarios. In the base case, supportive cognitive biases rapidly decline to zero within a shorter time frame. This suggests a swift decrease in supportive biases as the system progresses, likely due to the influence of opposing biases or other factors counteracting supportive biases.

In the LowerOpp scenario, the S-shape is highest, and supportive biases reach zero, indicating that lower opposing biases allow supportive biases to persist for longer. The absence of solid opposition means supportive biases decrease slowly, taking longer to reach the zero point.

The HigherCap scenario shows a line just below the LowerOpp case, suggesting that the higher capacity for biases slightly accelerates the decline of supportive biases. Despite the increased capacity for biases, the timing of the decrease remains similar to LowerOpp, indicating a similar dynamic in the influence of biases on supportive cognitive biases.

In the NegInflBase scenario, the decline in supportive biases is just below the base case, implying that the negative influence of behaviour changes and response to information hastens the reduction of supportive biases. This suggests that the added negative influences lead to a more rapid decline in supportive biases compared to the base case. Overall, these scenarios demonstrate how variations in biases, opposing biases, and negative influences can affect the rate of decline in supportive cognitive biases. The supportive biases were reduced to zero by approximately 40 months in the base case, with extended timelines in other scenarios.

The Mental Models simulation graph displays an upward bell curve-shaped growth, representing the evolution of mental models over time across various scenarios. In the base case, mental models peak at a median level before declining within a shorter time frame. This suggests that mental models also peak as biases and the need for sustainability increases; however, mental models begin to decrease as the system progresses and biases decline.

In the LowerOpp scenario, the peak to median occurs later, and mental models reach zero last, similarly to the HigherCap scenario. This delayed peak and prolonged duration suggest that lower opposing biases allow mental models to persist at higher levels for longer. The HigherCap scenario exhibits the highest peak, occurring at a time between the base case and LowerOpp. This indicates that the higher capacity for biases allows mental models to reach higher levels quickly but with a similar duration to LowerOpp. The NegInflBase scenario shows a peak similar to the base case, but the decline is slightly below the base case. This suggests that the negative influence of behaviour changes and response to information affects the trajectory of mental models, causing a faster decline compared to the base case. The peak occurs before 20 months in the base case, with delayed peaks for LowerOpp and HigherCap extending the total duration to approximately 50 months.

The Need for Sustainability simulation graph reveals a downward S-shaped growth, depicting how the perceived need for sustainability changes over time under different scenarios. In the base case, the need for sustainability declines rapidly to zero within a shorter time frame. This rapid decline may suggest that individuals perceive less urgency for sustainability as the system evolves, possibly due to decreasing biases and a shift towards more sustainable practices, also called the 'status quo' effect.

In the LowerOpp scenario, the S-shaped curve is the highest and reaches zero last, indicating that lower opposing biases result in a slower decline in the perceived need for sustainability. This may be because, with fewer opposing biases, individuals continue to perceive a need for sustainability over a more extended period. The HigherCap scenario shows a curve just below LowerOpp, with a similar decline pattern but reaching zero slightly earlier. The higher capacity for biases might mean that although there are more biases in the system, the decline in the perceived need for sustainability still follows a pattern similar to the LowerOpp scenario.

The NegInflBase scenario displays a decline just below the base case, suggesting that the negative influence of behaviour changes and response to information hastens the decline of the perceived need for sustainability. This could be due to the introduction of changes in individual behaviours or attitudes that lead to a faster reduction in the perceived necessity of sustainability. In the base case, the need diminishes to negligible levels by 50 months, whereas LowerOpp and HigherCap maintain it longer.

The Media Influence simulation graph displays two exponential growth curves, reflecting how media influence changes over time across different scenarios. The lines in the base case, HigherCap, and LowerOpp scenarios coincide with a positive exponential growth curve that gradually increases over time. This consistent pattern suggests that, in these cases, positive media influence continues to rise as biases and other factors in the system change. The steady increase may indicate that media influence is vital in shaping perceptions and behaviours, especially as biases evolve.

In contrast, the NegInflBase scenario shows negative exponential growth with a sharper decline. This suggests that the influence of behaviour changes and response to information results in a quicker reduction of media influence. This scenario highlights how negative influences, such as opposing information or behaviours that conflict with sustainable practices, can rapidly diminish the impact of media on individuals' perceptions and decision-making. Positive exponential growth is observed consistently over 100 months, whereas the decline in NegInflBase reaches near zero by 5 months.

These patterns illustrate how different scenarios can lead to varying trajectories of media influence within the system. Understanding these trends provides insights into the role of media in shaping sustainability attitudes and practices, as well as how different interventions can impact the system's evolution.

The different timeframes can be described as follows:

Bias development and saturation suggest that interventions targeting biases must be implemented early to prevent their entrenchment and reduce long-term negative impacts on decision-making. Sustainability urgency and intervention timing indicate that maintaining momentum for sustainability efforts requires sustained media influence and policy measures, especially during the first 50 months. The role of media influence emphasizes the critical role media plays in shaping perceptions over time. However, media impact wanes in scenarios with negative influences as early as 20 months, underscoring the importance of combating misinformation and maintaining consistent messaging. Behavioural shifts and supportive bias decline demonstrate how quickly supportive biases can erode without reinforcement. This finding highlights the need to reinforce positive behaviours and narratives to sustain long-term changes regularly. Mental model formation reflects the need to capitalize on this window for education and awareness campaigns to shape long-lasting perceptions and decisions.

These timeframes illustrate critical intervention points for policymakers, media campaigns, and industry leaders. Actions during the first 50 months, such as increasing public awareness, addressing cognitive biases, and reinforcing supportive biases, are pivotal in ensuring sustainable practices are adopted and maintained over time. The observed dynamics underscore the need for proactive and sustained efforts to drive systemic change in the Circular Economy. (Table 7, Table 8, Table 9)

The study provides expanded recommendations for mitigating cognitive biases in decision-making such as practical interventions for policymakers: Introduce regulations that counteract biases, such as incentives for adopting circular practices; Business leaders: Implement training programs that educate employees about biases and sustainability and consumers: Promote media literacy campaigns to increase awareness of biases in sustainable decision-making.

5. Conclusions

The stock and flow model simulation provided a comprehensive understanding of the complex interactions between cognitive biases, media influence, and sustainability-related behaviours within the Circular Economy (CE). This research aimed to investigate the impact of cognitive biases on stakeholders' decision-making processes and identify potential interventions to promote sustainable practices.

Key findings from the simulation revealed that cognitive biases significantly influence stakeholders' perceptions and decisions. These biases shape individuals' perceived need for sustainability, affecting their responses to information and changes in behaviour. Positive media influence increased willingness to change habits and adopt sustainable behaviours, while negative media coverage reinforced existing biases and resistance to change.

This study offers several innovative contributions by comparing these results with prior research. A comparative analysis of other studies, such as [43] and [95], provides the following: Unlike studies that isolate specific biases and disregard external factors, this research integrates multiple biases into a unified system dynamics framework with external interactions. This approach enables a holistic analysis of decision-making dynamics across CE phases. The combination of survey data and system dynamics modelling enhances the findings' validity, addressing criticisms of prior theoretical studies lacking real-world grounding, such as [38].

The practical implications of the research are substantial for policymakers, industry practitioners, and other stakeholders. By understanding the dynamics of biases and media influence on behaviour change, targeted strategies can be developed to promote sustainability

Table 7
SFD discussion on simulation parameters.

Approach	Discussion	Application
Equations	The SFD was modelled using equations describing how stocks change over time due to inflows and outflows. The system's dynamics were simulated by setting up equations for each stock and flow.	See formulas in Tables 5 and 6
Feedback Loops	Feedback loops play a crucial role in the behaviour of the system. Reinforcing loops (positive feedback) amplify trends while balancing loops (negative feedback) stabilize the system. These loops were modelled using equations and simulation tools.	See Table 4 and Fig. 7
Parameterization	Parameters such as inflow and outflow rates, biases, and response rates were defined and calibrated based on empirical data or expert judgment.	The survey data used in the system dynamics model were derived from qualitative analyses conducted using Atlas.ti, a qualitative data analysis software. These analyses provided insights into participants' attitudes, perceptions, and biases about sustainable production and consumption. The software helped quantify variables such as perceived need for sustainability, cognitive biases, and other related factors through coding and categorization.
Time Delays	Time delays may be present in the system, affecting how quickly changes in one variable impact others. Modelling these delays provided a more accurate simulation of system behaviour.	The available empirical data or survey responses do not provide sufficient information about the time for specific changes to occur in the system. As a result, incorporating specific time delays is challenging and less reliable.
Sensitivity Analysis	Sensitivity analysis was performed to assess how changes in key parameters or variables affect the system's behaviour. This analysis identified critical leverage points and potential interventions.	In each of the graphs in Figs. 10–14, clear trends are observed across different scenarios. The grey lines indicate scenarios with a maximum capacity for opposing biases were set at 2030, which is twice the base case value and represents one end of the range. The green lines denote the model's base values, aligning with the starting points discussed earlier in Tables 5 and 6. At the other end of the range, the red lines show scenarios with minimum opposing biases, set at nearly half the base case value, now adjusted to 100. The changes can also be seen in the previously mentioned tables for the blue lines depicted by the negative influence case.

Table 8
Key finding summary.

Key findings	Discussion
How biases create resistance to sustainability initiatives.	Cognitive biases such as status quo bias, confirmation bias, and loss aversion create significant barriers to adopting sustainable initiatives. These biases lead individuals and organizations to resist changes that disrupt familiar routines, underestimate the benefits of circular practices, and focus on immediate costs rather than long-term sustainability gains.
Which biases are most prevalent among different stakeholder groups.	Industry leaders often exhibit status quo bias, maintaining traditional production methods despite sustainable alternatives. Consumers tend to display anchoring bias, favoring conventional products over recycled or repurposed goods. Policymakers may experience optimism bias, underestimating the challenges in implementing CE policies.
How interventions such as policy changes and awareness campaigns can mitigate these biases.	Policy incentives, public awareness campaigns, and media influence play a critical role in counteracting biases. Financial incentives, such as subsidies for sustainable products, can help industry leaders overcome status quo bias. Consumer education and marketing strategies emphasizing the quality and affordability of recycled products help address anchoring bias. Transparent policymaking and stakeholder engagement reduce optimism bias, ensuring realistic policy implementation and adoption.
Cognitive biases' impact on CE	Status quo bias prevents firms from adopting circular strategies
Feedback loops influence outcomes	Positive feedback reinforces sustainable practices, while negative feedback amplifies resistance.
Media influence as a mediator	Exposure to sustainability-related media affects stakeholders' willingness to change.

and mitigate the impact of cognitive biases.

Recommendations for addressing biases in decision-making include increasing public awareness of biases, promoting media literacy, and creating supportive environments for sustainable practices. These measures can help stakeholders make more informed decisions and foster a culture of sustainability.

Policy recommendations include: policymakers should design regulations that counteract cognitive biases, such as incentives for adopting circular practices and penalties for wasteful behaviours. Media campaigns should prioritise public awareness campaigns. This should leverage the media's role in influencing perceptions, emphasizing the benefits of CE and debunking misconceptions. Industry action plans include: businesses should implement training programs to educate employees about biases and sustainable practices, fostering a culture of continuous improvement. One of the most pivotal recommendations is stakeholder collaboration. Cross-sector partnerships should align objectives, pooling resources to overcome shared barriers and amplify the impact of CE initiatives.

These measures, informed by empirical evidence, offer practical pathways to address cognitive biases and accelerate the adoption of CE principles.

The research contributes to a deeper understanding of the factors that drive or hinder the CE's sustainable production and consumption. The insights gained from the simulation provide a foundation for advancing sustainability goals and creating a more resilient and equitable future. By identifying leverage points and potential interventions, stakeholders can better navigate the complexities of the CE and promote more sustainable outcomes.

The academic contributions rely on expanding scholarly literature on sustainable systems, providing a nuanced perspective on biases and their impact. The paper has the potential to serve as a foundation for further research and academic discourse in the field.

Future research directions include exploring additional cognitive

Table 9
Dynamic behavior discussion summary.

Dynamic behavior	Discussion
How positive reinforcement accelerates CE adoption	Positive reinforcement loops play a crucial role in encouraging sustainable behaviors. For instance, when businesses successfully implement CE practices and receive positive consumer feedback, they are more likely to continue and expand these efforts. Similarly, government incentives for circular innovations can generate further investment in sustainable production, leading to self-reinforcing growth in CE adoption.
The role of media in shaping sustainability perceptions	Media exposure significantly influences stakeholders' attitudes toward sustainability. Positive media coverage of successful CE initiatives enhances public awareness and drives behavioral shifts. Conversely, misinformation or lack of visibility can hinder progress. Ensuring accurate and consistent messaging about CE benefits can reinforce positive behaviors and counteract biases that resist change.
Potential intervention points to mitigate negative biases	Several strategies can be employed to reduce the negative effects of cognitive biases in CE decision-making. These include targeted educational campaigns to address misconceptions, policy-driven nudges to encourage sustainable choices, and corporate strategies to redesign products with transparent information on environmental benefits. By identifying key leverage points, interventions can be tailored to counteract biases at different decision-making stages and across stakeholder groups.

biases, analyzing decision-making patterns across different stakeholder groups, and testing the model in diverse cultural and industrial contexts to improve generalizability.

CRediT authorship contribution statement

L. van der Linde: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **L. Pretorius:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Conceptualization. **R. Oosthuizen:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.101227.

Data availability

The data has been attached

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