

Manufacturers' implementation of circular economy practices and renewable energy sources in Saudi Arabia's industrial plants

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ABSTRACT

A dearth of research has addressed the growing integration of circular economy (CE) practices and renewable energy (RE) sources in industrial settings, motivating the commencement of the present study. The primary objective of this research is to document manufacturers' integration patterns of CE practices and RE sources in industrial plants. To fulfil this goal, the researcher convened two focus groups in Saudi Arabia. Each focus group featured five participants who owned, operated or researched facilities that implemented CE and RE. The findings suggest that four distinct integration patterns define how CE and RE are integrated in industrial settings: (a) biogas with remanufacturing, (b) solar power with recycling, (c) wind power and reducing and (d) the combined use of solar and wind power with more than a single CE practice. Further, results indicate a growing trend of using green practices such as green chemistry with CE practices in manufacturing. The study also reported the presence of numerous facilitators and barriers facing the integration of CE and RE. The current analysis contributes to the growing research on CE and RE aiming to improve sustainability.

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Circular economy; renewable energy; manufacturing; integration; sustainability

Introduction

Circular economy refers to the minimisation of waste in closed loop systems where materials are recycled, reused and reproduced throughout the extraction, production, consumption and discarding processes (Kharola et al., 2022; Ogunmakinde et al., 2021). Waste is unwanted material after consumption or the components of substances used in any phase of the manufacturing process are found unsuitable for recycling or reuse (Abduljaber, 2020; Dehghani et al., 2021; Mostaghimi & Behnamian, 2023). Increasingly, waste creates problems for manufacturers and governments alike (Mostaghimi & Behnamian, 2023; Salvia et al., 2021). On the one hand, companies need to deal with waste, spending more on its transport, treatment, or disposal (Matheson, 2022; Mukherjee et al., 2021). On the other hand, hazardous and nonhazardous types of waste pose serious threats to the environment, such as increasing CO₂ emissions of greenhouse gases in the atmosphere (Ogunmakinde et al., 2021; Salvia et al., 2021). Likewise, waste is a negative externality for communities that require local governments to spend money on addressing its potentially harmful consequences (Mihai et al., 2021; Righetti & Schremmer, 2022). Applying a circular economy minimises waste (Dehghani et al., 2021; Kharola et al., 2022; Ogunmakinde et al., 2021). One of the manifestations of circular economy implementation is the use of renewable energy sources. Figure 1 presents an overview of the circular economy construct.

Renewable energy refers to alternative natural ways of generating power other than traditional fuel sources such as oil, gas, or fossil fuels (Almagtome et al., 2020; Mutezo & Mulopo, 2021). The use of renewable energy minimises the number of materials used in its production and, most importantly, produces less waste, making such sources attractive points for circular economy advocates as well as government policymakers (Abduljaber & Onder, 2024; Dagilienė et al., 2021; Onder, 2022; Yu et al., 2022). Renewable energy reduces reliance on traditional utilities, minimises greenhouse gas emissions, and, in

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Figure 1. The circular economy (adapted from European Union Parliament, 2024).

optimal cases, keeps energy circulating from points of generation to consumption (Almagtome et al., 2020; Strielkowski et al., 2021). Thus, the integration of circular economy practices and renewable energy sources serves manufacturers in saving them colossal costs and governments in helping them achieve environmental sustainability objectives.

The integration of the circular economy and renewable energy in the manufacturing sector is on the rise (Mutezo & Mulopo, 2021; Yildizbasi, 2021). Integration achieves more gains on the environmental front of sustainability by decreasing CO₂ emissions and operations waste (Van Fan et al., 2021). Integration entails the incorporation of reduce, reuse, recycle and remanufacturing practices while maximising the use of clean renewable energy and assisting governments in reaching sustainability development goals and compliance metrics for international agreements (Biermann et al., 2022; Coscieme et al., 2021). Integration helps manufacturers reduce waste, decrease cost and minimise the consumption of virgin materials (Awogbemi et al., 2022; Ninduwezuor-Ehiobu et al., 2023). Such integrations refer to the incorporation of at least a single circular economy practice or more with one or more renewable energy sources (Bist et al., 2020; Hoang & Nguyen, 2021). For example, supplying food processing facilities with clean energy from biogas produced by an in-house anaerobic digestion plant using recycled animal waste is an increasingly observed integration between the circular economy and renewable energy (Chodkowska et al., 2021; Elroi et al., 2023).

By building on this framework, several successful examples highlight how the circular economy and renewable energy can be integrated across industries to generate substantial benefits. One such example is the use of biogas produced through anaerobic digestion in food processing plants. This process reduces waste while generating renewable energy, effectively closing the loop in the food industry. For instance, Chodkowska et al. (2021) described how food processing plants use biogas not only for energy generation but also as a method to address food waste, contributing to both environmental and economic sustainability. In addition, integrating solar energy into recycling facilities has proven effective in lowering CO₂ emissions. Elroi et al. (2023) demonstrated how solar-powered recycling operations significantly reduce energy consumption from fossil fuels, thereby minimising the environmental impacts associated with waste processing.

Moreover, waste-to-energy initiatives are increasingly becoming an integral part of CE and RE integration. Repsol's green methanol plant in Tarragona, Spain, is an exemplary case where municipal solid waste is converted into renewable fuels. This facility, which processes up to 400,000 tons of waste annually, is an excellent illustration of how waste can be transformed into valuable energy resources, contributing significantly to CO₂ emission reduction. Similarly, the use of sustainable community energy systems, such as in Woking Borough, UK, exemplifies how CE and RE can be combined in urban planning. Woking's system, which integrates solar photovoltaics, fuel cells and district heating, not only reduces reliance on traditional energy sources but also fosters the sustainable use of resources, highlighting the practical application of these principles in real-world scenarios.

Finally, recycling rare earth metals from electronic waste has become an important step toward ensuring the sustainability of renewable energy technologies. The QUILL research centre in the UK, for example, is developing green chemistry techniques to efficiently recover rare earth metals used in devices such as wind turbines and electric vehicles. By promoting the recycling of these critical materials, such initiatives help reduce dependency on primary resources, ensuring the continued advancement of renewable energy technologies. These examples collectively illustrate the significant potential for integrating the circular economy and renewable energy, leading to more sustainable practices that benefit the environment, economy and society.

This research paves the way to a novel area of research: the explicit and direct integration of circular economy practices and renewable energy sources in the manufacturing sector in Saudi Arabia. Previous research has failed to investigate such integrations at the system level or in emerging economies such as Saudi Arabia (Abid & Gafsi, 2025; Alhowaish & Alkubur, 2025; AlJaber et al., 2024). Additionally, this research presents a new integration map summarising how manufacturers integrated renewable energy sources with specific circular economy practices. Relatedly, this research introduces several new contexts for research in the integration field, such as biomass and recycling. The current investigation piqued the interest of future researchers and policymakers to further investigate renewable energy and circular economy integrations in industrial contexts.

Circular economy practices and renewable energy sources

To unpack the meaning of circular economy practices, a review of the literature concluded that different authors generated a variety of practices. Table 1 summarises the common circular economy practices mentioned in the extant body of written research on the subject. Some practices are more common in certain manufacturing contexts compared to others (Acerbi & Taisch, 2020; Jaeger & Upadhyay, 2020). Additionally, circular economy practices cover a wide range of areas, such as the supply chain, product design, functionality, tracking and disposal (Burke et al., 2023; Hazen et al., 2021). Similarly, a common list of renewable energy sources by the US Energy Information Administration (2023) is included in Table 2. Note that some concepts, such as green chemistry and nuclear energy, have generated considerable debate in the literature as to whether they are renewable or not and therefore were not included (Arefin et al., 2021; Silvestri et al., 2021). This research included the most comprehensive list of renewable sources given

Table 1. Circular economy practices.

Circular economy practice	Authors
Recycle	Awogbemi et al. (2022), Niyommaneerat et al. (2023), Yu et al. (2022).
Reduce materials and energy consumption	Calzolari et al. (2022), Mhatre et al. (2021), Ogunmakinde et al. (2021).
Remanufacturing of materials and goods	Chodkowska-Miszczuk et al. (2021), Elroi et al. (2023).
Reuse of materials	Almagtome and Al-Yasiri, (2020), Calzolari et al. (2022).
Waste minimisation processes	Mostaghimi and Behnamian (2023), Van Fan et al. (2021).
Renewable energy use	Calzolari et al. (2022), Kristia and Rabbi (2023).
Consumer awareness	Ioannidis et al. (2023), van Langen et al. (2021).
Repurpose	Chodkowska-Miszczuk et al. (2021), Ioannidis et al. (2023), Kristia and Rabbi (2023), Mutezo and Mulopo (2021).
Refuse	Dehghani et al. (2021), Kharola et al. (2022).
Education and training on circular economy	Mhatre et al. (2021), Mihai et al. (2021).
Environmentally friendly design	Burke et al. (2023), Ogunmakinde et al. (2021).
Environmental criteria for supplier selection	Hazen et al. (2021), Kharola et al. (2022).
Reverse logistics	Hazen et al. (2021).
Stakeholders' collaboration on circular economy	Ioannidis et al. (2023), Rogers and Deutz, (2021).

Table 2. US energy information administration major renewable energy types.

Solar energy
Geothermal energy
Wind energy
Bioenergy
Hydropower energy
Green chemistry
Nuclear
Biogas

the fact that manufacturers or policymakers may consider one type as a renewable energy source and act upon such an assumption.

Literature review

The existing studies in the literature on the circular economy and renewable energy focus on developed economies or Western countries (Abdirahman et al., 2025; Ahmadov et al., 2024; Alqahtani & Afy-Shararah, 2025; Alsaud et al., 2025; Bist et al., 2020; Islam & Ali, 2024; Mutezo & Mulopo, 2021). Few empirical investigations have touched on the implementation of either a circular economy or renewable energy, let alone their integration in Latin America, Africa, the Middle East and developing economies (Karaeva et al., 2022; Niyommaneerat et al., 2023; Ndoka et al., 2025). The current research brings forth the experiences of manufacturers in Saudi Arabia (Alyamani et al., 2024; Islam & Ali, 2024). Relatedly, the present research focuses on the actual journeys of policymakers and manufacturers in their endeavours of ameliorating the integration of the circular economy and renewable energy.

Much of the past research has failed to gauge the perceptions of important stakeholders such as manufacturers or senior public officials concerning the circular economy and renewable energy integration. Most studies have reviewed the literature without providing primary data on how key groups depict circular economy practices integrated with renewable energy (Calzolari et al., 2022; Mhatre et al., 2021; Khan et al., 2025; Alqahtani & Afy-Shararah, 2025; Alsaud et al., 2025). Similarly, existing reviews contain no information on how specific circular economy practices' integration with particular renewable energy sources are viewed in the eyes of policymakers or interested manufacturers (Nunes et al., 2023; Onder, 2021; van Langen et al., 2021; Wang et al., 2025).

For instance, stakeholders' attitudes toward the use of solar or wind power to generate clean energy for running recycling facilities are missing from the literature (Abdirahman et al., 2025; Wang et al., 2025). The present analysis not only informs readers about stakeholders' views on the integration of the circular economy with renewable energy but also provides detailed accounts of how policymakers view the progression of integration in the future (Alsaud et al., 2025).

Existing research on renewable energy and the circular economy lacks specificity concerning the technical, environmental, business and organisational elements of integrations or transitions (Kristia & Rabbi, 2023; Rajaonson & Chembessi, 2024; World Economic Forum, 2025; Circle Economy & Deloitte, 2025). Note that the present research addresses this deficiency in the literature. Studies analysing associations between circular economy practices and renewable energy sources fail to highlight the processes by which manufacturers shift from the 'take, make and dispose' model to the 'reduce, reuse, recycle and reproduce' model (Ioannidis et al., 2023; Laureti et al., 2024; Rajaonson & Chembessi, 2024; World Economic Forum, 2025). Relatedly, current research that blends aspects of a circular economy with renewable energy features that no crystal-clear pathway manufacturers take to achieve transitions (Alqahtani & Afy-Shararah, 2025; Ioannidis et al., 2023; Laureti et al., 2024; Ndoka et al., 2025). The present analysis not only delineates the various details of transitions and integrations but also paints clear roadmaps that real manufacturers have implemented, taking them from traditional systems toward circular models.

The study of CE and RE elements simultaneously is emerging in the engineering literature. Pan and Hashemizadeh (2023) developed an assessment framework based on CE approaches to identify RE implementation challenges. The authors validated the framework using a panel of experts that concluded the accuracy and consistency of the assessment approach. The findings suggest that the challenges of RE implementation vary across regions and countries. The analysis was limited in scope since it concentrated

on the Belt and Road Initiative countries without covering the industrialised economies. Such a field is expanding within the industrial ecology and sustainability literature (Abdirahman et al., 2025; Mhatre et al., 2021; Oughton et al., 2022; Pan & Ng, 2022; Sohail et al., 2025).

This research aims to explore how circular economy practices are integrated with renewable energy sources in the manufacturing sector. It seeks to identify specific integration practices, examine barriers and facilitators and understand stakeholders' perspectives on future integration pathways. The central research question guiding this study is: How are circular economy practices integrated with renewable energy sources in the manufacturing sector? Additionally, this study aims to map the transition pathways that manufacturers undertake to transform traditional facilities into circular economic systems powered by clean renewable energy.

This study adopts a qualitative research design to explore the integration of circular economy practices with renewable energy sources, with a particular focus on understanding the contextual dynamics that underpin this integration. Qualitative methods are ideal for investigating the complexities of such integration, as they allow for a deeper understanding of the setting, involved stakeholders, and objectives behind implementation, which are elements often overlooked in quantitative approaches (Busetto et al., 2020). While quantitative methods can provide insights into the strength and direction of relationships between variables, they fall short in uncovering the 'how', 'when', 'where', and 'why' of the integration process (Okoko, 2023). In contrast, qualitative approaches, such as focus groups, facilitate the gathering of rich, context-driven data highlighting key stakeholders' lived experiences, including factory owners, academics and government officials (Robinson, 2020).

Focus groups, which are structured group discussions, provide an effective platform for exploring participants' experiences, opinions and insights in a collaborative setting. In this study, focus groups are particularly valuable because they offer a dynamic space for capturing diverse perspectives and interactions among stakeholders. This setting allows the researcher to uncover the subtle, context-specific details of the integration process that may be overlooked by other methods. By encouraging group discussions, focus

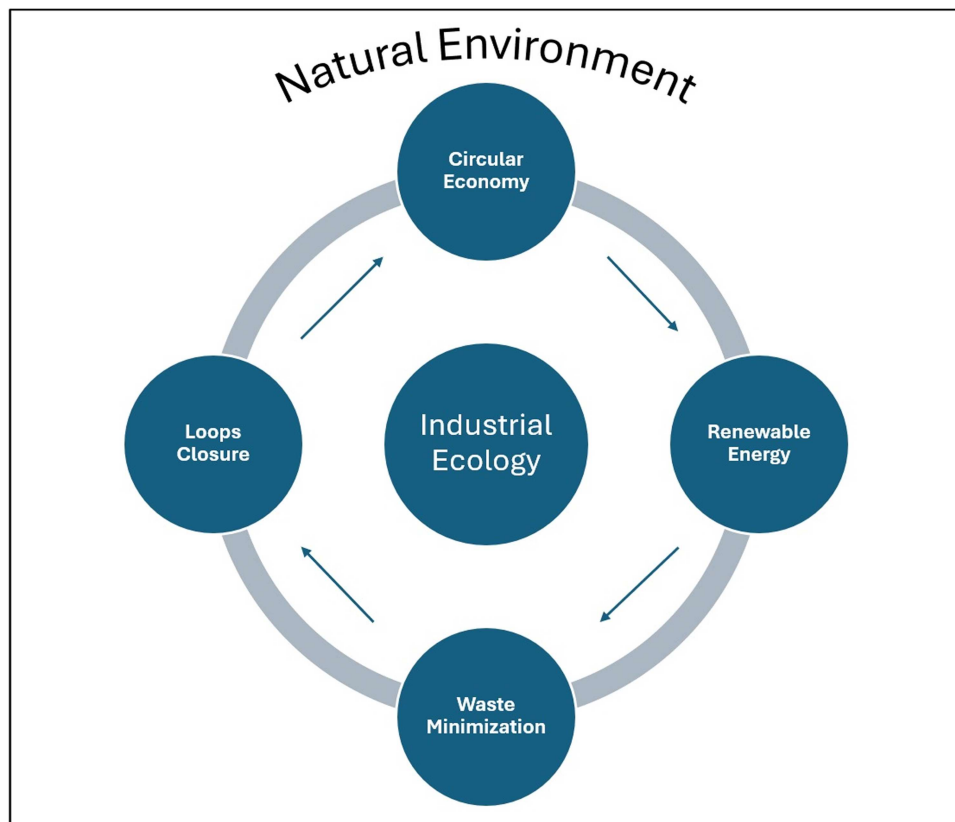


Figure 2. Theory of industrial ecology.

groups also reveal how participants' views evolve through interaction, providing a deeper understanding of the factors that influence the integration of circular economy practices with renewable energy sources.

Industrial ecology theory

Industrial ecology refers to the creation of sustainable systems of production that minimise environmental harm while improving socioeconomic conditions for communities globally (Akhtar et al., 2022; Van Ewijk et al., 2023). Industrial ecologists have begun with the assumption that current manufacturing systems are unsustainable (Agote-Garrido et al., 2023). Humans have depleted the earth's resources and created long-lasting problems such as pollution and global warming (Vasileva-Tcankova, 2022). At current rates of production and consumption, future generations are going to face shortages in resources and numerous problems (Glavič, 2021). Consistent with resource efficiency logic, industrial ecologists call for redesigning industrial and economic systems in ways that reduce material dependencies and close all potential loops in the system (Fei et al., 2021; Sun et al., 2025).

Figure 2 displays the logic of the industrial ecology theory underlying the present investigation. On the one hand, industrial ecology transcends many disciplines. Two such diverse realms are (a) economic systems and (b) energy cycles (Martín-Gómez et al., 2023). Industrial ecologists have attempted to redesign both systems to close unnecessary loops in the system (Agote-Garrido et al., 2023; Van Ewijk et al., 2023). Relatedly, the redesign process aims to minimise all types of waste. Past research has documented the ability of both the circular economy and renewable energy in accomplishing the two goals. The ultimate gain from reducing waste and maximising efficiency is the realisation of sustainability (Chaturvedi et al., 2023; Sharma et al., 2023). The present analysis follows industrial ecology theory.

Researchers in industrial ecology have investigated the use of energy and material systems and their impact on sustainability (Jie et al., 2023; Tanveer et al., 2022). This research focuses on two broad concepts that contribute to industrial ecological sustainability: renewable energy and the circular economy. The present study documents how manufacturers integrated renewable energy and a circular economy to make their facilities more sustainable. Industrial ecologists seek to improve current systems to make them similar to natural ecosystems (Agote-Garrido et al., 2023). This purpose leads to the identification of ways in which the current system could be reconfigured to minimise its negative impact on the environment and the economy. In this analysis, the study identifies how manufacturers have adopted circular economy practices and renewable energy systems to increase economic competitiveness while decreasing environmental impact.

Materials and methods

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Participants

A total of ten participants provided information in the focus group for the current investigation. A set of five participants were executives of manufacturing facilities. The remaining five participants were researchers and government officials on topics covering renewable energy and the circular economy in Saudi Arabia.

The choice of the two sets of participants broadens the width and depth of information obtained on integration. On the one hand, manufacturing executives could provide details on their experiences with implementing both concepts in their facilities. Additionally, owners or managers may share specific information on the facilitators or barriers that faced them during the implementation phase. Both groups received the same questions throughout the focus group sessions. On the other hand, researchers offer a more scientific discussion of why integration is expected or not. They possess specialised knowledge on specific renewable energy sources or circular economy practices and may share instances in which they studied meticulously within the country. Similarly, government officials have insights into the existing policies regulating both the renewable energy sector and the circular economy domain. More importantly, government officials provide specific information on the potential development of new institutions or funding for integration. Thus, the inclusion of multiple stakeholders in the qualitative research strengthens the accuracy and reach of information accessible to the researcher to perform the ultimate objective of the research, which is to provide a narrative on the integration between renewable energy sources and circular economy practices in Saudi Arabia.

Participants selection & data collection

In qualitative research, probability sampling is less critical than in quantitative studies, as the focus is on generating in-depth insights rather than statistical representations (Busetto et al., 2020). This study employed a nonprobability sampling approach, selecting ten participants—five manufacturers and five researchers/government officials—based on strict inclusion criteria. Manufacturers were identified through news stories and recent reports on the circular economy and renewable energy integration in Saudi Arabia, while researchers and officials were selected via academic literature and referrals. This approach ensured diverse perspectives on integration practices, challenges and opportunities. Table 3 presents the focus group prompts and questions.

Ethical approval & human participation

Cranfield University research ethics approval was obtained by the researchers prior to the data collection; the number of approvals was CURES/17446/2022. Written informed consent was obtained from all the participants in the study.

Data analysis

Thematic analysis in this study followed a structured six-step process to ensure a rigorous examination of the focus group data (Braun & Clarke, 2006). First, the researcher read the entire transcript three times to develop familiarity with key ideas and patterns. The second step involved initial coding, where a sentence-by-sentence approach was used, assigning concise labels to capture distinct ideas. This process was repeated independently, resulting in a high reliability rate of 98%. In the third step, similar codes were grouped into overarching themes, which were validated through a second classification attempt. The fourth step entailed defining each theme to clarify its conceptual boundaries and ensure alignment with the

Table 3. Focus group sessions questions.

Question 1: What are the circular economy practices implemented in your facility?
Question 2: What are the renewable energy resources used in your facility?
Question 3: Does your facility integrate circular economy practices and renewable energy sources? And how?
Question 4: What are the facilitators of circular economy integration with renewable energy in the Saudi manufacturing sector?
Question 5: What are the barriers of circular economy integration with renewable energy in the Saudi manufacturing sector?

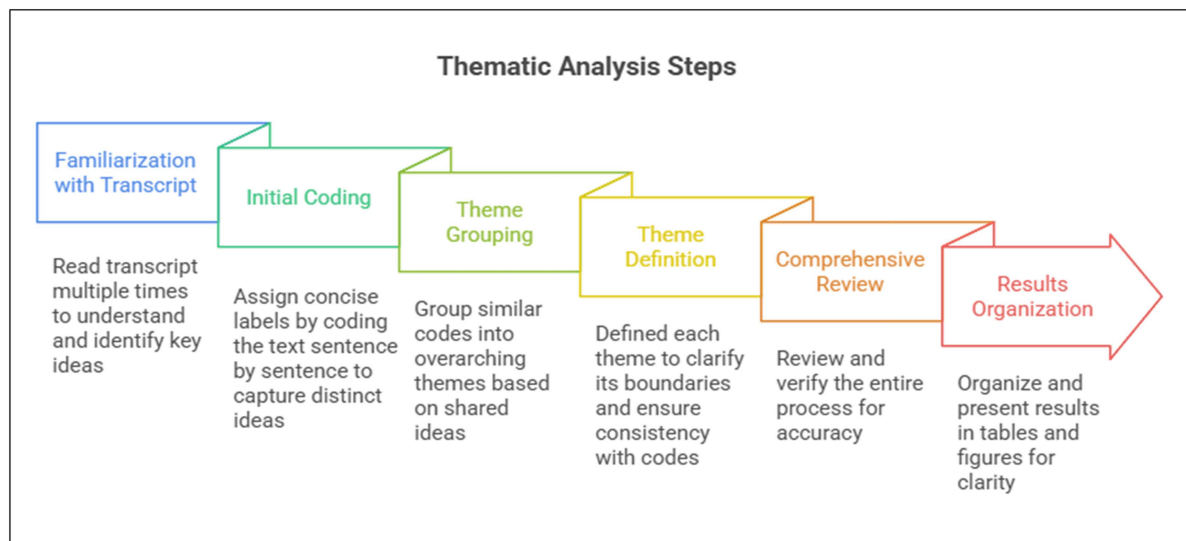


Figure 3. The six-step thematic analysis process.

underlying codes. A comprehensive review of all the previous steps was then conducted to confirm that the themes accurately reflected the original insights. Finally, the results were organised into tables and figures to enhance clarity and accessibility. This approach allowed for the distillation of a large corpus of text produced from over 20,000 words of focus group data into meaningful dimensions that explain patterns or trends in the information. The six steps of the thematic analysis process are visually summarised in Figure 3.

Note that the researchers manually coded the information collected from the focus group. Each researcher read the responses of the focus group sessions repeatedly to build familiarity with the information. Since thematic analysis concerns the holistic meaning of the text and not only the word frequencies, critical readings of the responses were also necessary. Thus, no software was used in the coding of information. The coding was manual. The results of the authors' coding procedures were very similar, adding credibility to the process of data analysis.

Limits to materials and methods

Like any other qualitative research, if the group of participants or set of questions were different, the content of the information or responses may have differed. While the coding process in the thematic analysis followed meticulous rigour and care, if other coders performed the analysis, some subjectivity in interpreting the information may have been more amplified. Further, all participants in the focus groups were males, which reflects the manufacturing sector in Saudi Arabia. If female participants supplied information to the facilitator, the topics, themes, or ideas in the responses could have differed.

Positionality

The first author is a public servant working on enhancing energy policy in the government of Saudi Arabia. Simultaneously, the researcher is a doctoral student at Cranfield University in the UK pursuing a degree in manufacturing engineering specialising in sustainable and clean production. Additionally, all the authors are interested in researching how circular economy practices are integrated with renewable energy. Thus, the authors decided to fill a gap in the literature by examining how the circular economy and renewable energy are integrated into Saudi manufacturing, a topic absent from the larger scholarly body of research on sustainable manufacturing. Thus, the topic of the paper is a shared interest of all authors who currently reside in the UK.

Results

The five questions in the focus groups asked participants to share their experiences and thoughts directly on the integration of circular economy practices and renewable energy sources in manufacturing settings. The answers to these questions referenced specific circular economy practices, such as recycling or reuse, as well as renewable energy sources, such as solar or wind power. Since the present research aims to provide a narrative describing how Saudi manufacturing facilities integrate a circular economy with renewable energy, the overarching defining element for the themes is the merger between at least one circular economy practice and one renewable energy source. For example, when the participant Adam shared the story of installing an anaerobic digestion plant adjacent to his food processing operation, the theme of bioenergy and reuse emerged. Note that anaerobic digestion represents bioenergy as a renewable energy source and reusing food compost represents the reuse of circular economy practices.

Concerning the integration of the circular economy into manufacturing in Saudi Arabia, four themes define how owners, managers, experts and policymakers have integrated the variety of CE practices into the manufacturing sector in the Kingdom. The ten participants in the focus group highlighted the incorporation of (a) circular supply chain practices; (b) R practices (i.e. reduce, reuse, recycle and remanufacture); (c) sustainability planning and (d) collaboration. Table 4 summarises the themes and their subthemes of the circular economy.

Saudi manufacturers have suggested the utilisation of CE supply chain practices. More specifically, two common manifestations of CE practices were prevalent in the focus groups' discussions: (a) reverse logistics and (b) partnering with green suppliers. On the one hand, Saudi companies began the implementation of country-wide reverse logistics programmes where consumers ship back used products to centres and warehouses. On the other hand, Saudi manufacturers are increasing their partnerships with green suppliers to utilise environmentally friendly materials and recycle difficult components such as plastics.

Reducing waste in landfills and within manufacturing processes was a shared objective shaping the future strategies of manufacturers, as reflected in the responses of the focus group participants. This priority aligns with the broader transition toward integrating circular economy principles in Saudi Arabia's manufacturing sector. Similarly, investment in recycling treatment facilities, such as anaerobic digestion tanks, was highlighted as a strategic approach rather than merely a regulatory necessity, reinforcing the role of recycling in industrial sustainability. The third recurring theme among participants was the reuse of materials, which was seen as essential for reducing waste and increasing recycling rates, thereby contributing to resource efficiency. Finally, remanufacturing defective products or returned goods emerged as a rising practice among manufacturers, further supporting the shift toward minimising raw material consumption and extending product life cycles.

Sustainability planning marks the third theme of CE practices integration into the manufacturing sector in Saudi Arabia. On the one hand, a number of senior government officials alluded to the utilisation of industrial symbiosis principles. More specifically, manufacturers pay more attention to the site's location, and the materials' shipment and the waste associated with the entire process. On the other hand, a few researchers highlighted the emphasis on the construction of eco-designs that help in protecting the environment. Manufacturers award further resources into the process of designing less intrusive products to minimise waste and its impact on the planet. Finally, government officials shared narratives about the

Table 4. Themes and subthemes of circular economy.

Themes	Subthemes
Circular supply chain practices	Reverse logistics Partnering with green suppliers
R practices (reduce, reuse, remanufacture and recycle)	Reduce Recycle Reuse Remanufacture
Sustainability planning	Industrial symbiosis The development of new eco-designs Construction of ancillary facilities
Collaboration	Stakeholders engagement Consumer feedback and experience

installation of facilities such as anaerobic digestion treatment plants adjacent to primary facilities to assist in the recycling and waste minimisation objectives' fulfilment adding further gains to environmental sustainability.

Collaboration constituted the fourth theme in the integration of CE practices into the manufacturing process. On the one hand, senior government officials engage stakeholders at all levels to improve sustainability gains and decrease waste. For instance, policymakers and government officials are incorporated into key decision-making processes for many manufacturers to ensure compliance with environmental standards (Abduljaber & Kalin, 2021; Onder, 2023). More importantly, government officials highlighted the increasing importance of consumer feedback to manufacturers' decisions (Onder, 2019a, 2019b). Consumer demands for green products and recyclable goods are being incorporated by manufacturers' top leadership. In summary, manufacturers' collaboration with stakeholders to enhance product quality while preserving the environment is on the rise. Figure 4 summarises the circular economy practices in Saudi manufacturing settings.

With respect to the integration of renewable energy into the manufacturing sector, researchers and senior government officials have pinpointed five frequently cited themes across the focus group discussions. The themes were (a) the simultaneous use of RE sources, (b) solar power, (c) wind power, (d) bioenergy and (e) comprehensive sustainability vision. Each theme was derived from a collection of codes. A code referring to a singular idea within a sentence. The sentences were derived from the focus group transcript. The researcher read the full transcript, assigning a single code to each sentence. Once the list of codes was prepared, each set of codes related to a larger idea was classified together. Each grouping of codes refers to a theme. For example, the list of codes 'use of wind turbines' and 'implementation feasibility' refer to the broader theme of 'wind power' because participants referenced wind power elements in their responses. Table 5 summarises the themes and their subthemes of renewable energy.

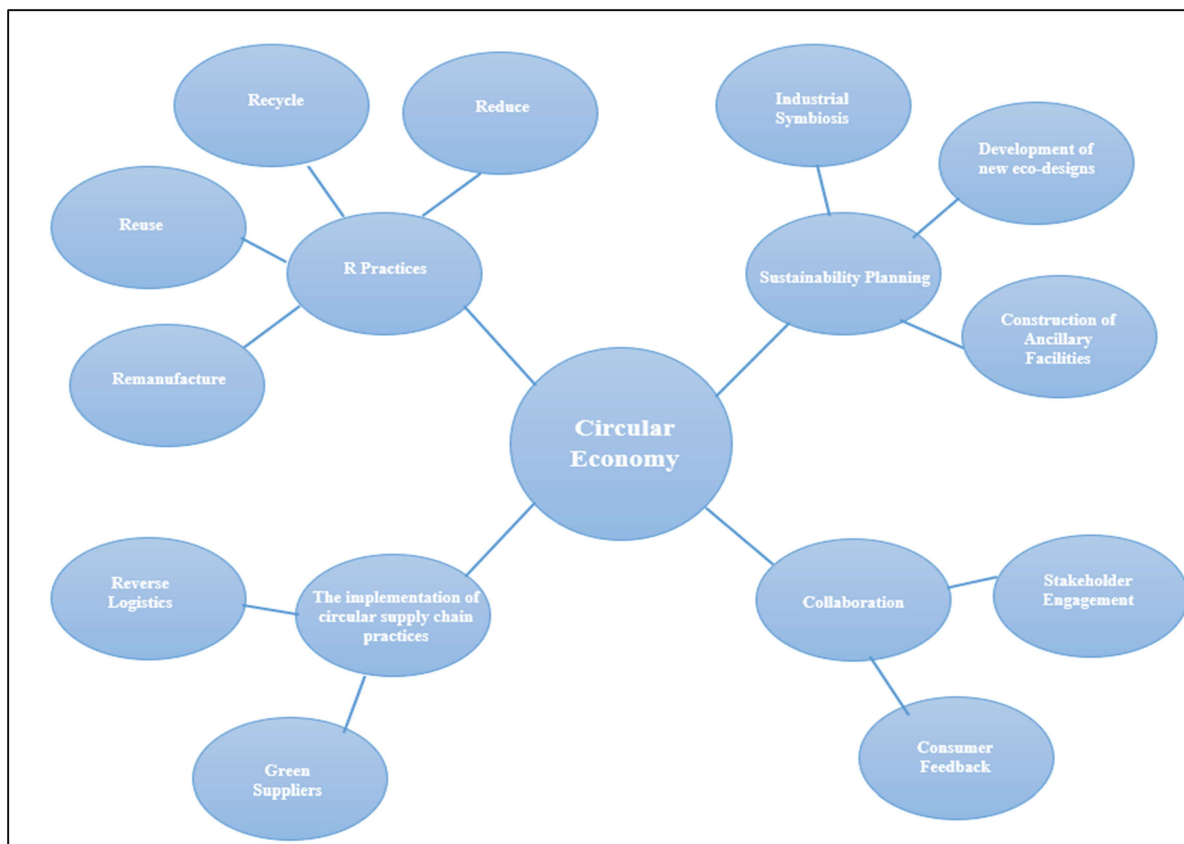
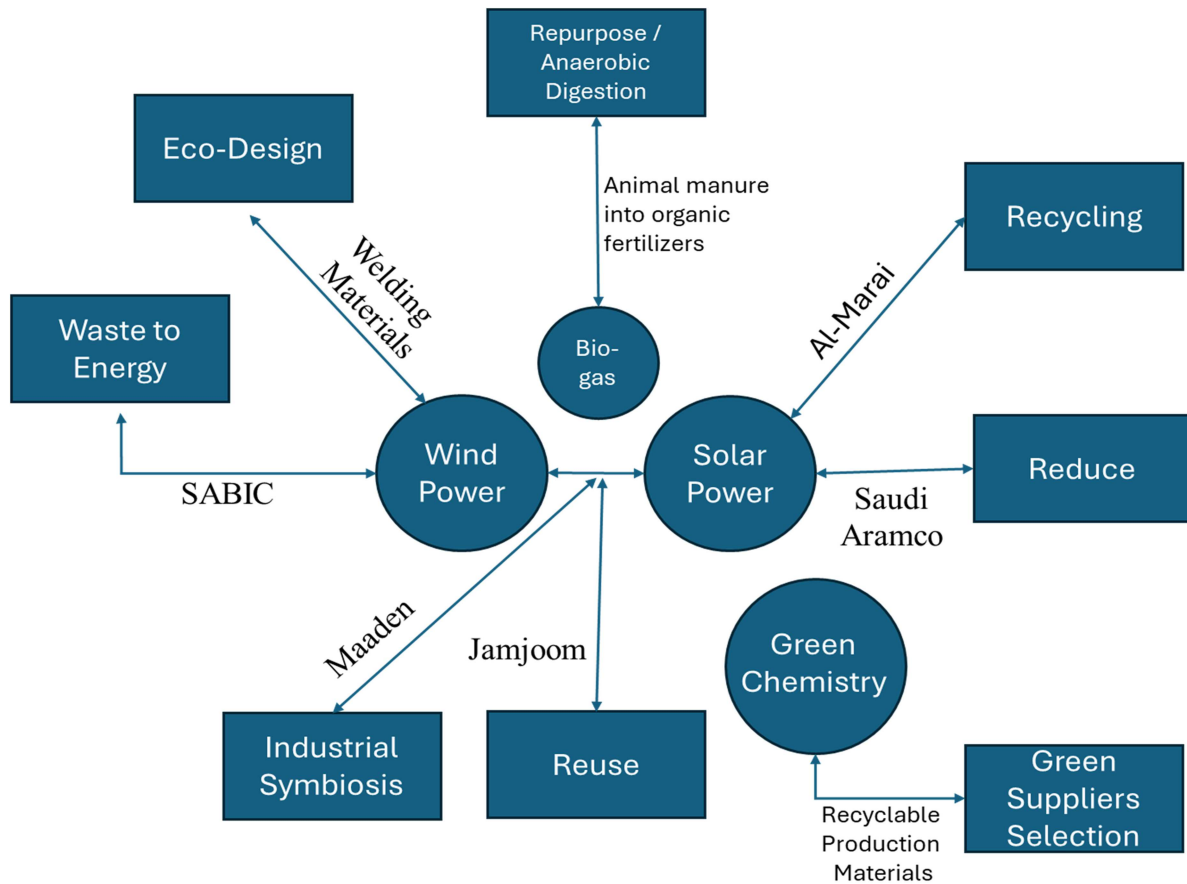


Figure 4. Circular economy practices in Saudi manufacturing settings.

Table 5. Themes and subthemes of renewable energy.

Themes	Subthemes
The combined use of multiple renewable energy sources	The integration of solar and wind power Establishment and extension of hybrid projects
Wind power	Green chemistry Use of wind turbines Implementation feasibility
Solar power	Solar panels Workspace utilisation
Comprehensive sustainability vision	Green initiatives Green purchasing and manufacturing Advanced technology deployment
Bioenergy	Anaerobic digestion Waste to energy plants

**Figure 5.** Integration patterns.

Researchers often highlight the combined use of renewable energy sources in the manufacturing process at the same facility. The most frequent simultaneous use was the integration of solar and wind power to supply clean energy to manufacturing facilities and reduce utility expenditures. Further, researchers have noted the increasing expansion rate of renewable energy use across manufacturing facilities. For instance, facilities that already utilise solar power sought partnering with wind power suppliers to supplement their energy sources. Further, existing manufacturers that utilise either solar or wind power began to invest in waste to energy facilities to aid in the clean energy supply pipeline expansion. Similarly, plastic manufacturers have invested in green chemistry, where multiple energy sources are used to recycle or process plastic waste, minimising its impact on the environment. Green chemistry facilities also incorporated the combined use of solar and wind power, thereby manifesting the simultaneous usage theme.

Senior government officials pointed to the increasing utilisation of wind power. On the one hand, the owners identified Dumat Al-Jandal, a large-scale wind generation project, as the source of power to much

of their energy consumed throughout the manufacturing process. Similarly, experts highlighted the importance of the country's investments in wind turbines and partnerships with the manufacturing sector to decrease reliance on traditional sources of energy. Further, current manufacturers have suggested the performance of feasibility studies to expand their usage of wind power.

The most frequently mentioned renewable energy source integrated with manufacturing in Saudi Arabia is solar power. Manufacturers shared stories about their purchases and deployment of solar panels to decrease their reliance on the grid. Similarly, manufacturers pointed to their utilisation of solar energy produced in the country's large-scale facilities across all regions. More importantly, researchers have indicated the increasing investment in the restructuring of workplaces such as facilities to fit solar power use. For instance, many manufacturers have expanded rooftops to fit more panels. On the other hand, other manufacturers expanded factory floors to accommodate more panels supplying energy to facilities.

Few senior government officials and researchers have emphasised the investment in bioenergy as a potential renewable source supporting the manufacturing process in Saudi Arabia. One of the most noticeable trends in the discussions of the respondents was the evident increase of anaerobic digestion plants. More specifically, agricultural manufacturing facilities, as well as food treatment plants, highlighted the investment in anaerobic digestion tanks in helping them remanufacture waste into fertilisers. By the same token, a few policymakers suggested the expansion of investments in the area of waste to energy plants. Food compost was one of the most cited examples of how waste could be transformed into energy or other products.

Another common theme in the discussions of respondents was the comprehensive sustainability vision concerning renewable energy and manufacturing. Policymakers prioritised the power of green initiatives in supplying clean energy to manufacturers (Abduljaber & Kalin, 2019a, 2019b). Large-scale projects such as NEOM's hydrogen plant, as well as other solar/wind power governmentally funded facilities, constituted multiple references in the focus group discussions contributing to the country's sustainability vision. Similarly, the incentives for green purchasing and manufacturing offered by the government to manufacturers represented another important component of the holistic sustainability vision.

Figure 5 shows the integration patterns between renewable energy sources and circular economy practices within the manufacturing sector in Saudi Arabia. One of the emerging integration patterns manifests in the increasing use of anaerobic digestion. The respondents suggested that food plants repurpose waste to generate biogas, methane, which supplies portions of the floor with electricity. Further, discussions in the focus groups indicated the use of food waste as inputs for organic fertilisers. Thus, bioenergy as a renewable source of power is linked with repurposing or remanufacturing, an integral CE practice, in Saudi manufacturing realms. Note that the source of information used to construct Figure 4 originated from participants' narratives, replying to the focus group question asking about how CE and RE are integrated into the manufacturing sector in Saudi Arabia.

Solar power's integration with the circular economy manifested in recycling materials, as well as reducing reliance on traditional energy sources. On the one hand, respondents highlighted large corporate attempts to increase the utilisation of solar panels to reduce utility bills. By the same token, increasing the use of photovoltaics helps manufacturers in supplying energy for recycling facilities. For instance, the largest dairy manufacturer in the country invested heavily in solar power to supply clean power to its new recycling operations. Therefore, solar power as a renewable source of energy is intertwined with two important R practices in the circular economy: recycling and reducing.

Participants noted the connection between green chemistry as an emerging approach for the generation of clean and renewable energy and green supplier diversity. Manufacturers of plastics highlighted firms' active attempts in partnering with trusted third-party vendors specialising in recycling using green methods. For instance, manufacturers invest in the purchase of new highly sophisticated technical machines capable of recycling parts of plastics that rely on solar energy provided by the newly installed panels at facilities. Manufacturing's proactive approach to hiring green suppliers and treatment facilities reduces the impact of plastics on the environment.

Focus groups' conversations pinpointed the close link between wind power and two significant circular economy practices: eco-designs and waste-to-energy methods. On the one hand, Saudi manufacturers of turbines and their components have increasingly invested in designing green products. More importantly, large-scale wind power projects have sought partnerships with vendors specialising in green products to

minimise waste throughout maintenance processes. By the same token, wind power provided clean energy to newly established waste-to-energy facilities at large conglomerates such as SABIC.

One of the clearest integration patterns between renewable energy and circular practices is the combined use of sources, as well as practices in the same sector or context. For instance, many participants emphasised the simultaneous use of solar and wind power in supplying facilities or factories with energy. For instance, the geographic location of facilities maximises the use of solar and wind power in facility operations. Such a strategic choice conforms to the industrial symbiosis logic, where manufacturers place their physical operations near their energy and virgin material supplies. In a similar vein, a manufacturer known for its implementation of reverse logistics utilised solar and wind power to supply its reuse and remanufacture programme.

Table 6 presents the facilitators of renewable energy and circular economy integration in the Saudi manufacturing sector. First, the respondents echoed the importance of institutional support in accelerating integration. On the one hand, respondents suggested that strong governmental support in the form of regulations and collaboration assists in accelerating the integration process between renewable energy and the circular economy. On the other hand, the participants agreed that leveraging institutional support requires close coordination and serious stakeholder engagement.

When pressed on unpacking the meaning of stakeholder engagement, the participants referred to three broad practices: public-private partnerships, consumer awareness education and training and consultancy initiatives. The respondents believed that for circular economy practices to be further integrated into renewable energy adoption, the government must partner with trusted companies to establish exemplary large-scale projects. On another front, many respondents indicated that consumers and manufacturers do not truly understand the meaning of integration. Therefore, the government and private sector firms need to invest more in the education and training of potential consumers to recognise the strategic importance of integration. Finally, integration is highly technical, and consultancy services may decipher its convoluted nature, making it accessible and appealing in the eyes of investors and existing corporations.

Integrating a circular economy with renewable energy in manufacturing requires heavy investments in advanced technology. The respondents expressed their belief that if companies allocate more resources to artificial intelligence, integration becomes more automated and less costly. Further, participants indicated that the human capital needed to achieve effective levels of integration is absent from the manufacturing sector. To facilitate integration, more technical training, as well as research and development investments, are needed.

Unanimously, all participants agreed that financial investment constitutes a significant facilitator of integration. On the other hand, the government needs to provide grants and funding for integration projects. On the other hand, the government needs to create an ancillary environment suitable for encouraging investments in integration, such as the offering of fiscal incentives. Similarly, the government is urged to invest in large-scale private projects aimed at increasing integration between renewable energy and the circular economy.

Like the recognition of facilitators, the respondents noted many hindrances to the integration process of renewable energy and the circular economy (see Table 7). First, participants asserted the slow growth of human development dimensions related to integration. For instance, many manufacturers expressed their

Table 6. Facilitators of renewable energy and circular economy integration.

Themes	Subthemes
Institutional support	Strong government support Collaborative endeavours Strong regulations
Stakeholders engagement	Public-private partnerships Consumer awareness and training Consultancy services
Technology investment	Artificial intelligence Technical research and development Human capital technology programmes
Financial aid	Fiscal incentives Public financial backing Grants and subsidies

Table 7. Barriers of circular economy integration and renewable energy.

Themes	Subthemes
Human development	Lack of human capital Duplicate efforts Resistance to change
Infrastructure	Outdated facilities Lack of technical support teams Absence of logistics systems
Economic barriers	Absence of consumer engagement Cost Uncertain return on investment
Inconsistent and unstandardised regulatory environment	Policy variance Inconsistent standards Lack of sectoral collaboration

frustration in finding appropriate talent for managing transitions toward renewable energy implementation. Relatedly, the respondents shared employees' resistance to change. Many facilities desire to implement clean energy initiatives; however, stakeholders are resistant to changing operations.

Another limiting factor to the acceleration of integration is the outdated manufacturing infrastructure in Saudi Arabia. Many manufacturing facilities still operate on old floor plans using legacy systems and machinery. Additionally, manufacturers are afraid of investing in new technical systems because maintenance teams and resources are not readily available if needed. Few participants suggested the need to fly expert teams from other regions in the country or even abroad to address technical errors or downtimes for newly installed systems such as wind power generation infrastructure.

Economically, integration is hefty. The implementation of circular economy practices or the utilisation of renewable energy systems in manufacturing is costly, dissuading many investors and stakeholders from the pursuit of such an enterprise. Relatedly, integration seems to be uncertain in the eyes of many. Investors do not quantify the gains from updating existing operations. Therefore, many potentially promising modernising integration moves are thwarted given the unclear return on investment.

Finally, participants recognised the volatile inconsistent regulatory environment concerning integration. While new policies urge manufacturers to adopt green initiatives and endeavours, they lack specificity. In addition, many government bodies have published differing standards and criteria for meeting sustainability goals related to the circular economy and renewable energy. Policy variance causes confusion among serious investors interested in integration. Most importantly, the respondents suggested a lack of agency collaboration when integration efforts are in place.

Discussion

The emergent finding from Saudi Arabia in this research with respect to the barriers facing manufacturers' integration of the circular economy and renewable energy is consistent with past research (Försterling et al., 2023). Similar to this research, Van Opstal and Smeets (2023) reported that external impediments such as regulatory constraints, knowledge gaps among consumers and society at large, and the unavailability of affordable accessible technology hindered businesses' abilities to transition from traditional to smart operations running on circular economy frameworks, including renewable energy use. By the same token, this research highlighted the importance of consumer, stakeholder and interagency collaboration in overcoming challenges to the adoption of a circular economy and renewable energy transitions, as similarly found in, who reported that the integration of CE and RE requires active engagement from all parties involved in the enterprise. Thus, barriers to implementing integration seem to remain constant regardless of development levels or geography. More importantly, barriers appear to be closely related requiring refined approaches and policies that consider the complexities underlying associations among the varying challenges (Van Opstal & Smeets, 2023).

The results from the present study have noted the significance of the integration effects on long-term CO₂ emissions. Past research has established a strong statistically negative association between renewable energy consumption rates and CO₂ emissions (Ishaq et al., 2022). The participants in the focus groups suggested an increase in the use of clean energy in manufacturing, relying on solar, wind and biological energy sources. Such observations align with the recent decarbonisation initiatives Saudi Arabia witnessed

with respect to CO₂ emissions contributing to the country's fulfilment of its obligations to global treaties on climate change (Krane, 2022). The rate of renewable energy consumption is driven by strong governmental support, as evident in this analysis. Therefore, integrations of renewable energy and circular economy practices assist governments in minimising CO₂ emissions in the long run, contributing to their overall sustainability goals.

The results of the current study partially confirm trends in renewable energy transition scholarship and observations. On the one hand, this qualitative project noted the emphasis on solar and wind power as the most frequently utilised renewable energy sources like other economies around the world (Davis et al., 2020; Hassan et al., 2024). On the other hand, geothermal and hydroelectric power transitions were not recognised as potential sources for helping manufacturers transition from linear economies to circular economies. One potential explanation for such an observation is the absence of public or private investments in geothermal or hydroelectric large-scale projects. Another possible reason behind the participants' failure to mention either geothermal power or hydroelectric projects is the lack of exposure to either of the sources (Amoatey et al., 2021).

Noticeably, participants in this investigation emphasised recycling, reducing, remanufacturing and reading as the most frequently applied circular economy practices, similar to past observational research (Rogers et al., 2021; van Langen et al., 2021). Studies of the circular economy have indicated that the R practices are the most popular or common circular strategies firms or manufacturers apply during transitions from traditional operations to smart factories. Recycling appeared to preoccupy participants' thoughts, as it is the most cited practice in circular economy research (Dragan et al., 2024; Papamichael et al., 2023). By the same token, some practices, such as reverse logistics and eco-design, have received much less emphasis compared to the R practices, as the case in past research. Such trends note the need in revamping education and training programmes or professional development workshops on the circular economy, noting the importance of all practices. Similarly, conceptual delineations of circular economy frameworks must award sufficient attention to practices other than the 4Rs or 5Rs (Papamichael et al., 2023; Rogers et al., 2021; van Langen et al., 2021).

Unlike Ndoka et al. (2025) and Alyamani et al. (2024), who list a number of obstacles facing either the implementation of a circular economy alone or a single renewable energy source in manufacturing facilities, the present study adds the integration component to the existing literature. Previously, a few authors have addressed the integration of a circular economy and renewable energy, and this paper shares numerous on the ground success stories of integrating different circular economy practices and renewable energy sources. For instance, the use of anorexic digestion to provide clean energy to power food processing facilities is a newly growing phenomenon in the integration literature documented in this analysis.

Another contribution of the current manuscript is the application of integration to a new case. Previous researchers focused on the industrialised world (Rajaonson & Chembessi, 2024; Circle Economy & Deloitte, 2025; Giganti & Falcone, 2025; World Economic Forum, 2025). The present analysis shows that emerging economies such as Saudi Arabia reflect a similar pattern to other economies vested in the increasing implementation of a circular economy and renewable energy. On another level, the current manuscript shatters the myth that clean production is a common feature of industrialised economies (Alqahtani & Afy-Shararah, 2025; Alsaud et al., 2025; Alyamani et al., 2024; Islam & Ali, 2024; Ndoka et al., 2025; Wang et al., 2025). Saudi Arabia is implementing mega projects unobserved in other nations reflecting high degrees of integration, such as the circular carbon economy.

One of the novel contributions of this study is the presentation of distinct patterns of integration in a simplified visualisation. Figure 5 presents the distinguishable amalgamation of CE practices and RE sources. One of the newly identified patterns is the use of combined RE sources with the same CE practices. For instance, many manufacturers utilise solar wind power to run recycling processes. Additionally, the figure identifies two new integration patterns previously unexplored: (a) biomass and CE practices through anaerobic digestion and (b) the rise of green chemistry with CE practices such as waste-to-energy. Such identification is likely to generate further research within the integration field.

Another primary contribution of the research is the novel scope of study. Most researchers have analysed the association between CE and RE from a parochial lens, studying a single resource or practice.

Thus, the settings of previous studies did not cover the universe of CE practices or RE sources simultaneously in manufacturing. Oftentimes, researchers introduce discussions of a single CE practice or RE source without fully appreciating its integration as a potential important entity. The present research began by highlighting integration as a new concept. While still at the rudimentary level of conceptualisation, the integration of CE and RE as whole systems deserves further attention, and the present analysis grounded this idea.

Policy implications

Policymakers in Saudi Arabia need to incentivize research and development in renewable energy emerging fields such as hydraulic power, microorganism synthesis power generation platforms and geothermal energy. The evidence in the current paper notes the colossal investments that Saudi government agencies have made in solar and wind power. For instance, the Public Investment Fund (PIF) owned by the Saudi government financed large-scale renewable energy projects such as the Sudair Solar PV project. Nevertheless, investments in large-scale biomass or bioenergy projects have not surfaced, recognising the opportunity for further improvements in such sectors. Saudi energy policymakers may establish new research and development grant programmes soliciting proposals for actual experimental energy facilities using biological, geographic or other utile energy systems. Similarly, the government may enhance its educational programmes by sponsoring more doctoral students pursuing research in top universities around the globe specialising in renewable energy.

A primary policy implication of this research is the need for proactive public engagement campaigns to increase awareness about the benefits and opportunities associated with the integration of the circular economy and renewable energy. Policymakers could establish continuous channels of communication, knowledge sharing and networking groups on the roles of the circular economy and renewable energy within the manufacturing sector. Simultaneously, the government needs to establish a task force or a steering committee responsible for accelerating the rate of integration, thereby stimulating interest and actual implementation within the private sector.

Future research directions

The design and development of training programmes for operations personnel and the manufacturing workforce is a primary future research area. The focus groups highlighted the absence of available or appropriate human capital or development frameworks for preparing existing employees and workers for the adoption of a circular economy or renewable energy. Thus, future researchers are urged to develop easily implemented and accessible education and training workshops suitable for contemporary manpower to facilitate transitions from legacy or traditional practices into sustainable approaches within the manufacturing sector. Relatedly, future researchers may assist educational institutions in the development of vocational training courses or modules to be offered to potential or current manufacturing workforces featuring hands-on experiential components in the operation of circular economy practices or renewable energy system installation or production.

A crucial territory of future research is the intersection of artificial intelligence and the integration of renewable energy with the circular economy. Artificial Intelligence (i.e. AI) offsets some of the concerning prohibitive costs while accounting for the limits of human capital through optimised deployment. The investment in AI not only saves monetary resources in the long term but also optimises efficiency in energy usage adding more gains toward sustainability. Embedding circular economy practices such as reducing energy, recycling materials, remanufacturing of returned goods and reverse logistics in the AI realm helps manufacturers transform from traditional energy sources to renewable outlets. Relatedly, future researchers could develop policy frameworks that integrate AI into the integration of circular economy practices and renewable energy sources. Policy proposals specifying how AI technology could be amalgamated with circular economy practices may accelerate the transformation toward sustainable energy utilisation within the manufacturing sector.

Limitations

While the research presents valuable insights into the integration of the circular economy and renewable energy in manufacturing, the qualitative nature of the design weakens the generalisability of the research to other countries. Within Saudi Arabia, the results of the research are transferable given the variety of respondents and the depth of answers obtained in the study. Nevertheless, the results may not transfer to other countries because of the varying degrees of manufacturing development and geographic distribution of renewable energy sources. Thus, the results of the research suffer from low generalisability.

Conclusions

Saudi manufacturers have integrated eight circular economy practices with three renewable energy sources across four patterns. In addition to the three renewable energy sources, clean energy sources are highlighted presented by green chemistry. The integration of biogas with repurposing to remanufacture food compost turns waste into organic fertilisers in food and agricultural product facilities. Solar power merger with recycling and reduces the desire to generate clean energy running portions of the recycling and production process. Similarly, the integration of wind power with waste-to-energy and eco-design suggested an attempt to minimise waste throughout the manufacturing life cycle. Finally, the combined utilisation of solar power and wind energy coupled with the deployment of industrial symbiosis and reuse pointed to the smooth operational performance, decreasing logistical and personnel requirements in the manufacturing process.

The findings of the thematic analysis also reported four primary barriers facing manufacturers in their pursuits of integration, which were: (a) human development, (b) infrastructure, (c) economic barriers and (d) inconsistent and unstandardised regulatory environment. By the same token, focus group conversations alluded to the presence of four facilitators that assisted manufacturers in implementing the integration between the circular economy and renewable energy represented by (a) institutional support, (b) stakeholder engagement, (c) technology investment and (d) financial aid. In summary, Saudi manufacturers utilise (a) wind power, (b) solar power and (c) biogas as clean energy sources in manufacturing and (a) recycling, (b) reducing, (c) green supplier selection, (d) reusing, (e) industrial symbiosis, (f) waste to energy, (g) eco-design and (h) anaerobic digestion as circular economy practices within their operations.

One of the promising future study area concerning the circular economy's integration with renewable energy is the existence of potential social corporate responsibility initiatives. In other words, private sector stakeholders have strengthened their commitment and endeavours toward increasing the use of renewable energy sources and circular economy practice. Nonetheless, few studies have systematically examined how the private sector has integrated renewable energy with a circular economy. Researchers may survey firms' executives on their future and programmes that blend the circular economy with renewable energy. Similarly, qualitative studies may investigate how the private sector has assisted governments in fulfilling sustainability goals with a special focus on circular economy implementation within renewable energy sectors. Also, policy researchers may develop new programmes that firms may implement to accelerate the integration process. A common denominator in all such aforementioned research endeavours is the specification of links connecting circular economy practices with renewable energy sources.

The most important contribution of the present research is the demonstration of real applications for integrating circular economy practices with renewable energy sources in manufacturing. Further, the research highlights the variance in which different economies rely on distinct patterns of integration. For instance, none of the participants echoed the use of geothermal or whereas research in developed countries documented cases of such uses in manufacturing. Most importantly, the findings shatter the perception that circular economy integration with renewable energy sources is a developed economy or country practice by showing how small and medium facilities are investing in smart, clean manufacturing processes within emerging economies. Relatedly, the present analysis showcases how a human agency equipped with knowledge and innovation can overcome structural challenges like outdated technology and absence of strong governmental support through the creation of cutting-edge integrations contributing to the building of an authentic circular economy.

Author contributions

CRedit: **Mohammed Farhan Alqahtani**: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft; **Mohamed Afy-Shararah**: Supervision, Validation, Writing – original draft, Writing – review & editing; **Konstantinos Salonitis**: Validation, Writing – original draft, Writing – review & editing.

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The data that support the findings of this study are available from the corresponding author, M.A., upon reasonable request.

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