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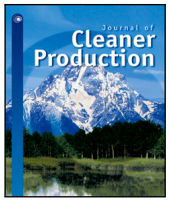

Review

Transition from linear to circular economy in pavement engineering: A historical review

Zhuhuan Liu *, Nicole Kringos

Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden

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ABSTRACT

Navigating the complex pavement system to the circular economy is a multi-dimensional and time-consuming endeavour. Obstructed by lock-in mechanisms of the prevailing "take-make-dispose" linear mode, the current circular economy studies in pavement infrastructure often focus only on one certain type of practice, featured by fragmentation from a system perspective. This study presents the first systematic literature review on the historical development trend of the circular economy concept in the pavement sector based on the collected 59 studies from 2006 to 2022. This review also identifies the soft (regulatory, social/environmental) and hard (technical, market/economic) drivers of- and barriers to the paradigm shift, aiming to coordinate the existing fragmented findings and facilitate the future systemic implementation of the circular economy. The synthesis of the results indicates that the underdeveloped technical guidance and legal system are inhibiting the paradigm shift to the circular economy. Furthermore, the authors argue that the importance of transparent and standardized data along the whole supply chain should be highlighted. Ultimately, this paper suggests that a welcoming environment set by the road authorities is crucial for innovation and entrepreneurship, as well as for constructing a system where stakeholders can confidently take responsibility and initiative.

1. Introduction

As one of the pillar infrastructure industries, the road infrastructure sector is believed to have a key role in the sustainability transition of modern society with its 25% share of global greenhouse gas (GHG) emissions (United Nations, 2021). Being the most significant physical assets of the road infrastructure, pavement systems have received non-negligible attention regarding their sustainability potential. Globally, the pavement industry has been working towards emission reduction for many years, although the current linear model that was established during the Industrial Revolution has certainly limited efficiency in achieving sustainable goals at multiple levels (Stahel, 2016; Sariatli, 2017). The essential concept of this prevailing traditional economy model is generally summarized as "take-make-dispose" (Ellen MacArthur Foundation, 2013; Sariatli, 2017), which means collecting the raw materials that are needed, manufacturing the products that are to be sold, selling the products to the consumers, who then dispose of them as wastes.

What cannot be neglected is that shifting from the linear mode inheres an innovation-intensive process of systemic reconfiguration and adaption (De Jesus and Mendonça, 2018) . Today's world is a complex system of interacting elements (Saaty, 2001), featured by the technological revolution of two centuries under a frame of complicated stakeholder networks, policies and incentive structures (Unruh and Carrillo-Hermosilla, 2006). Together with globalization and changing societal behaviors, these elements individually and interactively exacerbate the complexity of the systemic sustainability transformation (Saaty, 2001). Thus, transitions toward the circular economy imply considerations of multi-dimensional interactions and structural changes of the existing unsustainable system that has stabilized through the natural lock-in inertia of the linear model with its established economies of scale and sunk costs in machines, infrastructures and competencies. Thus, shifting to an incentive system that is based on long-term sustainability values will typically induce bad financial performance in the short run due to the high initial investment (Wu and Pagell, 2011). Consequently, the authorities will have to play an essential role in internalizing the externalities to material extraction and waste disposal to reform the existing regulatory, accounting, and fiscal frameworks.

The pavement sector is one of the clear examples that are suffering from several lock-in mechanisms. The long lifespan of the physical road assets and the substantial amount of sunk cost in machinery for asphalt production, maintenance, and rehabilitation, even in competencies determine the energy demand related to the road system for many decades after their construction (Seto et al., 2016). For instance, as noted by many previous studies, cold recycling technology

* Corresponding author.
E-mail addresses: zhuhuan@kth.se (Z. Liu), nicole.kringos@abe.kth.se (N. Kringos).

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Acronyms

CDW	Construction and Demolition Waste
CIR	Cold In-place Recycling
CML	Centrum voor Milieukunde Leiden
CR	Crumb Rubber
DOT	Department of Transportation
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
HIR	Hot In-place Recycling
HMA	Hot Mix Asphalt
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCIA	Life Cycle Inventory Assessment
MP	Material Passort
NRA	National Road Authority
PET	Polyethylene Terephthalate
RAP	Reclaimed Asphalt Pavement
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

has the potential to be a more environmentally sustainable option in comparison to traditional hot recycling technology (Giani et al., 2015). in which the mineral parts that constitute 80% of the bulk, need to first be heated up to be mixed. However, due to a combination of tradition, risk minimization, lack of investigation and guidelines as well as road contractors' sunk cost in hot recycling appliances, the dissemination of cold recycling has been greatly restricted (Xiao et al., 2018). Together with institutional lock-in from the social and political dimensions, it further reinforces the carbon-intensive status quo, even though it results in not only suboptimal performances from a perspective of common goods but also a direct loss of opportunity to innovate cross-disciplinary with other sectors that are moving forward. The development of smart roads for future mobility is a clear example in this case. The spread of autonomous vehicles is one of the most pronounced innovations in automotive and transportation engineering during the last two decades with a potential benefit on fuel efficiency, driving safety improvement, and mobility accessibility increase (Litman, 2020). To enable the real-life utilization of autonomous vehicles, the current pavement system has to be equipped to allow immediate data change for communications with the vehicles and with service managers (Trubia et al., 2020). An outdated pavement infrastructure will not only obstruct the ongoing innovation-oriented development in the transport sector but also impair the possible sustainability effects that could be accomplished by autonomous driving from a system perspective, considering the additional damages that autonomous vehicles may cause and the negative effects that damaged roads may have (such as extra emissions due to rolling resistance and downtime). Despite these challenges, the transition process is hindered by factors like inadequate legislative support, technical guidance, and limited budget allocation. Consequently, achieving sustainability goals at a systemic level within the pavement sector remains a daunting task.

Under the call for a new and more sustainable model for the whole socio-economic operating standard, the circular economy has emerged as a promising approach, dominating the discussions on sustainable development. The nascent conceptualization of circular economy took place in the 60s when the American economist Boulding (1966) came up with the "spaceman" economy theory, depicting "the earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution". In light of Boulding's contribution, Pearce and Turner (1990) introduced the term "circular economy". They argued that the "open" consuming economic system should be replaced by a "closed" sustaining system to achieve the equilibrium between resource extraction and waste discharges.

The concept of the circular economy has gained a significant amount of attention from academia, industry, policymakers, influencing governments, and nongovernmental organizations at local, regional, national, and international levels (Geissdoerfer et al., 2017). However, as noted by Stahel (2016), realizing a circular economy in practice necessitates concerted efforts across society. Research and innovation play a crucial role in assessing the life cycle impacts and costs of products, designing products with reusable frameworks, and convincing decision-makers of the imperative for sustainable transition (Stahel, 2016). The industry must take the responsibility to raise the awareness of the public and advocate for more sustainable options. Policies are required to internalize the external costs of material extraction and other relevant emissions and contamination from a product's whole life cycle. Meanwhile, as the growth of the Internet of Things (IoT) technologies will eventually boost the transition, policymakers have to come up with a plan to solve the potential dispute over the ownership, accessibility, and liability of data. Shifting from a linear to a circular mode entails complex processes and formidable challenges at social, technological, and commercial levels. However, the whole society needs to be prepared to take on the challenges as the rapid climate change forces us to.

In the pavement sector, the ongoing transition from a linear to a circular framework represents a novel and evolving paradigm with several hindrances due to the complexity of the pavement system. This paper contributes to the field by providing the first systematic review of cutting-edge circular economy practices within the pavement sector. By synthesizing the latest insights and challenges, it aims to stimulate discussions for defining the development directions and advancements required for systemic sustainability transformation. A summary of the main contents and structure of this review work is presented in the flowchart in Fig. 1.

2. Overview of circular economy development in pavement engineering

The roadway network serves as an important economic component, facilitating the movement of freight and commodities (FHWA, 2015). In addition, it is also considered a key social component with its offered accessibility to schools, work, and services. While society became aware of its essential roles beyond the socio-economic aspects, the environmental significance of road infrastructure has come into the limelight, including material extraction, GHG emissions, energy consumption, and waste generation. Stakeholders in the pavement industry recognize the sustainability potential and are urged to adopt circular economy principles, seeking cleaner production technologies (FHWA, 2015). Current alternatives mainly focus on recycling reclaimed asphalt pavement (RAP) and incorporating various wastes into pavement materials. This section offers a brief historical overview, covering recycling practices in asphalt design, sustainability evaluation through life cycle studies, and future proposals for systemic circular economy implementation in pavement engineering.

2.1. Historical practices in asphalt design and production

RAP recycling is a popular circular economy practice in the pavement sector, driven by factors like the 1973 oil crisis and subsequent binder cost increase in 2006 and 2008 (Copeland et al., 2011). According to the European Asphalt Pavement Association, an average of 91% of RAP was recycled across 13 countries in 2020, with 64% reused for its original purpose and 27% repurposed as aggregates for unbound layers, leaving only 9% landfilled (EAPA, 2020). Howbeit, the average European value does not reflect the realities in some countries. For instance, Austria and Romania achieved 100% recycling of RAP; in contrast, Croatia had more than half of their RAP landfilled.

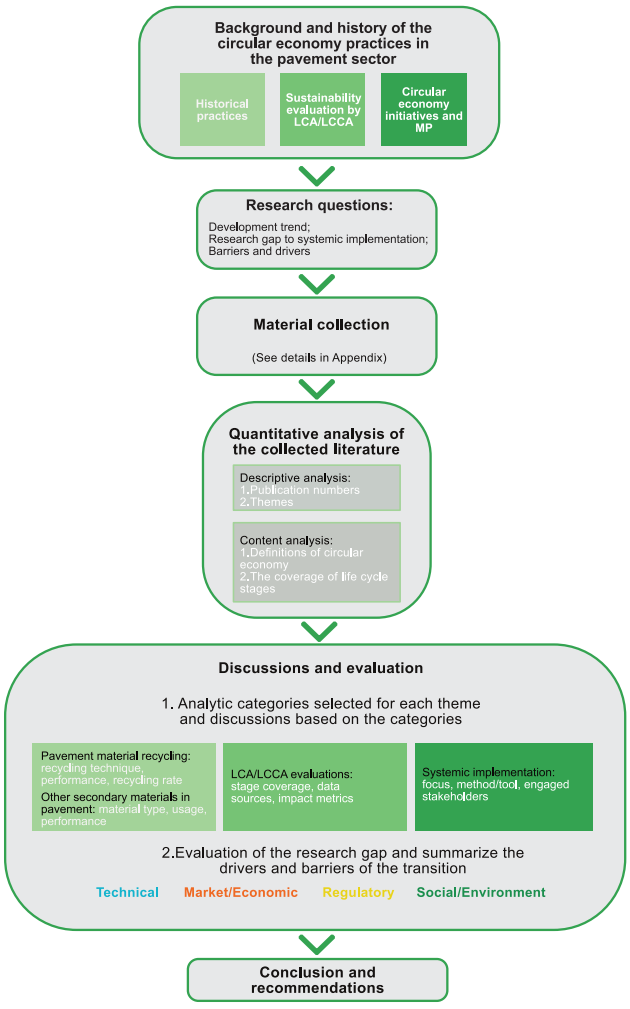


Fig. 1. Flowchart of the review structure.

In the U.S., RAP has been successfully used with almost 0 percent being landfilled. However, the percentage of RAP in asphalt mixtures is still typically less than 15% wt. because at this level no extra tests or additional applications for approval are needed. Although several equipment and technologies can be adopted to modify the production process, the additional costs for upgrading plants and the concerns about the blending results of the mixtures containing high RAP content are still setting barriers for the contractors and road agencies. Even though it seems like the current road projects have managed to recycle most of the generated RAP, the approach of recycling is not truly sustainable as RAP is often applied for a degraded function (Tarsi et al., 2020), meaning a considerable amount of economic value loss.

Another noteworthy attempt is the use of secondary materials like crushed glass, tires, sludge, and plastics in asphalt mixtures to address waste disposal issues. Among the types of secondary materials that have been used in asphalt binders and mixtures, introducing crumb rubber (CR) and plastics as modifiers and additives has gained increasing attention due to their engineering performance, economic and environmental benefits. The substantial amount of waste tires generated annually around the world is a huge environmental threat not only because of its pressure on space for stockpiling and disposal but also the possible leaching toxic compounds incurring soil, groundwater, and surface water contamination at the landfills (Yadav and Tiwari, 2019; Tushar et al., 2022). Many laboratory studies have reported that CR-modified asphalt could present better resistance to rutting and better low-temperature performance than traditional asphalt. Therefore, CR has been considered a low-cost and more environmental-friendly alternative for producing polymer-modified asphalt. However, it has also been pointed out by scholars that the properties of CR-modified asphalt binder highly depend on the chemical characteristics of the binder and the CR, as well as the percentage and particle size of the CR, also the interactive temperature and time (Lee et al., 2008). Additionally, concerns have also been raised regarding the environmental impacts and health risks of producing and constructing asphalt pavements containing CR (Zanetti et al., 2015). Nevertheless, there has only been limited research attention being paid to the quantification of the actual socio-environmental effects of this practice.

Likewise, waste plastic is another by-product of our rapidly growing economy that is usually treated with landfill and incineration. In 2018, 27 million tons of plastic arrived at the landfills in the U.S., accounting for 18.5% of all of their municipal solid waste (US EPA, 2018). Challenged by the eco-toxicity and health risks to animals and humans brought by plastic, the international community has proposed a wide range of strategies to mitigate “White Pollution” (Darko et al., 2023). Prior researchers found that waste plastics could act as a replacement for virgin polymers with similar modification results, leading to multiple benefits such as reduced temperature susceptibility and rutting potential. Simultaneously, the use of waste plastic as modifiers also offers advantages from environmental and economic perspectives as it saves costs, conserves natural resources, and alleviates waste disposal issues owing to the non-biodegradability of plastic materials (Joohari and Giustozzi, 2020). With its promising sustainability performance, waste plastic has been used as an asphalt modifier in various countries worldwide. In Australia, China, India, the Netherlands, the U.S. and the UK, plastic-modified asphalt has been adopted for road construction in several pilot projects (Ma et al., 2021). Besides various investigations on its engineering performance, using reclaimed polymetric waste in asphalt products has also been evaluated in an increasing number of projects regarding its environmental and economic effects by the means of life cycle assessment (LCA) (Li et al., 2019).

Circular practices extend beyond secondary recycling, with research exploring the end-of-life stage. A long-term vision of pavement recycling is deemed necessary, considering further recyclability and possible toxic emissions from external waste materials at high temperatures, instead of emphasizing the seeing gains.

2.2. *Towards sustainable pavements: Sustainability evaluation by applying life cycle principle*

Adoption of the circular economy essentially contributes to the integration of sustainability into business models and social behaviors, supporting companies and society to achieve environmental quality, economic prosperity, and social equity without sacrificing any of the dimensions (Kirchherr et al., 2017; Brändström and Saidani, 2022). With the aim of evaluating how circular economy strategies support sustainability, the concept of circularity is often used and circularity metrics are introduced to condense the complexity of the assessment. However, circularity is still a novel measurement without adequate implementation in road pavement projects (Mantalovas and Di Mino, 2019). Meanwhile, there is still a lack of consensus on how circularity should be measured in general (Harris et al., 2021).

At a micro level, economic performance often constructs the fundamental metric of circularity. The life cycle principle was introduced to pavement engineering under such a context, starting with the development of life cycle cost analysis (LCCA). In the 1960s, the National Cooperative Highway Research Program in the U.S. promoted the application of LCCA principles to pavement design guidance. Over time, it gained broad recognition as a more comprehensive evaluation of pavement alternatives and helped decision-makers to identify the most cost-effective design options (Babashamsi et al., 2016). Simultaneously, environmental sustainability is another crucial perspective of circularity. With LCCA being the precedent, LCA was introduced

to the pavement infrastructure by Roudebush (1996) and Häkkinen and Mäkelä (1996) in 1996. Since then, there has been an extensively growing body of literature utilizing LCA to evaluate the environmental sustainability of the pavement system. Based on a standardized framework, LCA allows comparisons between products and services, which can effectively capture burden-shifting issues in the system (Mantalovas and Di Mino, 2019). More importantly, it is possible to adjust its framework to give valuable insights into the impact of circular economy strategies.

In the earlier days, LCA was primarily used to compare the environmental impacts of asphalt and concrete pavements to quantify which type of pavement was more energy efficient (Santero et al., 2011; Inyim et al., 2016). More recently, with new techniques being developed and adopted for pavement production, recycling, and maintenance, LCA has also gained popularity among the studies that are examining the systemic environmental impacts of the new techniques (Giani et al., 2015). From a global aspect, LCA has been widely accepted by not only the academia but also the road authorities and contractors as a standard tool to deliver the environmental investigation results of asphalt products and in-situ or in-plant recycling processes. More details about how LCA has been integrated into different national road authorities' strategies can be found in the following Section 2.3.

A nonnegligible defect of life cycle studies, however, is the data accuracy. Noted by many previous studies (Santero et al., 2011; Liu et al., 2022a), a trustworthy life cycle report requires exhaustive inventory data retrieval. Unfortunately, most pavement life cycle studies do not acknowledge the uncertainty brought by missing case-specific inventory data. Furthermore, as a consequence of data limitation, a considerable portion of the existing LCA literature gives emphasis merely on GHG emissions and energy consumption while overlooking the other impact categories which are also crucial concerns for material recycling in the pavement industry. In addition, even though LCA and LCCA have the capability of preventing the burden-shifting problem, it is only valid when the system boundary is carefully defined. Data limitations and niche interests hinder holistic insights across the pavement life cycle, with limited attention to stages beyond manufacture and construction, leading to simplified or omitted components.

2.3. Smart pavement transformation: Circular economy initiatives and material passports in a digitized era

While general circular economy policies exist in various countries, specific legislative guidelines for circular pavements are limited. However, a few attempts shall be highlighted. With their focus on road pavements, Garbarino et al. (2016) proposed a list of evidence-based criteria for the European Commission, emphasizing circularity and sustainable standards in road projects. The report highlighted trade-offs between energy recovery, cost savings, and transportation of recycled materials.

As many road agencies have realized the drawbacks of information asymmetry during pavement design, a considerable variety of pavement-related LCA tools have been released by national road administrators (NRAs), including EKA (Trafikverket, 2016) and Klimatkalkyl 7.0 (Trafikverket, 2021) from Sweden, EFFEKT and VegLCA 5.10B (Statens vegvessen, 2022) from Norway, DuboCalc 5.0 (Rijkswaterstaat, 2017) from the Netherlands, ECORCE 2 (IFDTTAR, 2013) from France (no longer available online), and asPECT 4.2 (UK Transportation Research Laboratory, 2014) from the U.K. An increasing number of nations have chosen to enforce the inclusion of LCA through several phases of road projects such as Sweden, Norway, and the Netherlands. Meanwhile, another feature that makes the LCA tools from these three countries' NRAs (Klimatkalkyl, DuboCalc and VegLCA) stand out is the verified Environmental Product Declaration (EPD) databases they utilize. An EPD documents the life cycle environmental impacts of products in a standard form with being verified by a third party. For instance, an asphalt manufacturer could choose to establish an EPD on its asphalt mixture by registering through EPD International AB (2022) (Sweden), EPD Norge (2022) (Norway), and Institut Bauen und Umwelt e.V. (IBU) (2022) (Germany). Following the ISO 14,000 series of standards, EPDs are created to facilitate material choices and make environmentally informed decisions. Beyond EPDs, there is still a need for continuous information updates after the material has formed a component of the system (Adisorn et al., 2021) as the EPDs will not feature the characteristics of the asphalt material after it is being exposed to traffic load and climatic conditions.

Advancing the establishment of comprehensive databases of EPDs marks a promising step toward integrating environmental considerations into decision-making processes (Götz et al., 2022). To enable the change, accessibility to structured information are crucial encompassing both material-related factors (such as composition, performance, and flow) and non-material-related factors (including cost, energy performance, and geography), given the enduring lifespan of road pavements. A possible instrument that offers a platform and repository for storing, linking, and providing such information to relevant actors along the value chain is called a materials passport (MP) (Heinrich and Lang, 2019). The term "material passport" can be traced back to McDonough and Braungart (2003). It is worth mentioning there are other equivalent terms such as "product passport"(O'Shea, 1995), "recycling passport" (Hesselbach et al., 2001), and "nutrient passport" (Hansen et al., 2013). However, based on a review of 127 articles on MPs and other competing concepts, MP is found to be the most used one (van Capelleveen et al., 2023). Thus, in the rest of this study, MP will be adopted to represent the circular economy passport to avoid potential confusion.

Industries indicate that an MP should be built on widely recognized systems that already exist, such as EPDs, instead of having it start from scratch (Götz et al., 2022). One of the challenges for MPs is to feed material usage information continuously upon the existing EPDs while facilitating free communications among stakeholders, and ensuring data interchangeability for optimal spatiotemporal material distribution. More importantly, an MP must be based on clearly defined material recyclability and provide case-specific information to understand potential recycling or reusing hindrances. In addition, it has to support innovation and future-oriented business models with clear incentives to encourage recyclable materials to be recycled in an optimal approach.

The promotion of MP in the broad construction sector began in 2016 when the EU Horizon 2020 project Buildings as Material Banks (BAMB) introduced the concept of digital MP to the building sector. From a global aspect, the Netherlands is leading as a pioneer in the entire built environment field, publishing guides and recommendations for MP applications (Platform CB'23, 2020). While a few studies have presented successful case studies utilizing the MP for design optimization (Honic et al., 2019a), stakeholder management (Honic et al., 2019b), circularity assessment of materials (Heisel and Rau-Oberhuber, 2020) in building projects, this concept is still relatively novel for the pavement sector with few case studies that have not been well documented.

The transition to a holistic circular approach to handling road pavement assets is obstructed by a plethora of challenges, including the inadequate technical and mechanical performance of the recycled materials, budget restrictions, limited accessibility to the information, lack of incentives, missing administrative support and unclear legislation guidance, together with the deficient communication among all the stakeholders (Mantalovas et al., 2020). In order to understand these underlying challenges and assist the systemic implementation of the circular economy in the pavement sector, there is a need for studies that reflect the current practices and identify the knowledge gap and absent information towards a closed loop in the pavement sector by answering the following research questions based on the existing literature:

- What is the historical trend development of circular economy practices in the field of road pavement engineering?

- What perspectives have been mainly studied regarding these practices?
- Based on previous studies, how is the overall sustainable performance (technical-, cost- and environmental-) of the traditional material recycling and reusing technology for road pavements?
- To achieve the future systemic upgrade to the adoption of materials passport, what information and knowledge gaps are to be bridged?
- What are the drivers of- and barriers to-the transition to a circular mode in pavement engineering?

3. Methodology

This study aims to reflect on the historical development of the circular economy concept in the pavement sector and discuss its future opportunities and challenges brought by the digitized era. A systematic literature review is conducted in this study to investigate the existing literature with qualitative and quantitative evaluation, offering a transparent and reproducible analysis process and evidence-based synthesis (Tranfield et al., 2003).

After formulating the research questions in Section 2, a 4-step framework by Mayring (2016) is applied to identify the publications to be included and categorize them according to their topic-specific structural dimensions, which contains:

1. Material collection: Defining and delimitating of the materials to be collected and the unit of analysis.
2. Quantitative analysis: Using quantitative methods to analyze the formal aspects of the defined materials such as publication numbers and geographical distribution of the authors.
3. Category selection: Selecting the structural dimensions and analytic categories that are to be applied to assess the collected materials.
4. Material evaluation: Evaluating the materials on the basis of the structural dimensions in order to identify the relevant issues to be addressed.

3.1. Material collection

The details regarding the material collection process are provided in the following part of Section 3.1.

3.1.1. Selection of databases

To reach a wide range of academic journal articles, the citation databases Web of Science, Scopus from Elsevier are used. At the same time, regarding the technical innovation in the circular economy concept in road engineering (ex. material passports), industrial practices can be the ones leading the pioneering work ahead of academia in some cases. Thus, Google Scholar is also employed to ensure a broader delivery of grey literature that is still research-based, including reports and policy papers made by government organizations, "think tank" institutions and private companies.

3.1.2. Selection of keywords

First of all, the keywords "pavement" and "road" are used to confine the review to the relevant subject of pavement engineering. The basic line under the selection of the rest of the keywords is to capture a broad range of research works that can reflect the historical trend change of the circular economy practices within the field instead of focusing on one certain type of practice. Therefore, specific terms like "cold in-place recycling" are avoided while general terms "recycling" and "reclaiming" are chosen. The term "reusing" is excluded as its generality leads to an extensive number of publications. The whole search sequence is listed below:

- ("pavement" OR "road") AND ("recycling" OR "reclaiming" OR "end-of-life" OR "circular economy" OR "Environmental Production Declaration" OR "EPD" OR "material passport*")

The search is executed based on all possible combinations among the above-mentioned terms, and the searching fields are restricted to the title, abstract, and keywords.

3.1.3. Inclusion and exclusion criteria

The keywords in Section 3.1.2 are applied for searching relevant studies and December 31st, 2022 is the latest inclusion date. The searching is limited to English publications to avoid possible language bias. The collection is limited to journal articles, conference papers, book and book chapters, and reports while presentations, comments, and technical notes are excluded. It is worth mentioning that pavement material passports are established on the development of the interdisciplinary knowledge of pavement engineering and information technology. Considering the importance of proceeding papers in the community of information technology, conference proceedings are given credits as well. The subject area is also used as a quick filter to delimit the results. Irrelevant topics such as medicine, psychology, astronomy, and agriculture are excluded from the screening process. Furthermore, the keyword "road" occasionally presents in the phrases "road map" and "road to...(e.g. circular economy)", which often leads to research in other fields instead of pavement engineering. Thus, "road map" and "road to..." are also set as exclusion criteria. Because of this study's special interest in the conceptualization of circular economy in the pavement sector, studies focusing purely on numerical modeling and thermodynamics are not included in the following analysis. At this phase, there are 64 studies collected from Web of Science and Scopus. Due to the limited development of EPD and MP in the field, a "snowball" method is applied to reach more potential research by using Google Scholar, which has added 2 theses to the collection. Among these 66 publications, 7 review articles are identified. Nonetheless, these reviews have overall focused on the technical aspects of recycling and reusing technologies, which do not overlap with the interests of this study. According to Tranfield et al. (2003)'s recommendations, a systematic literature review should be drawn upon primary data to create a study in its own right. Thus, these review articles are excluded from the following analysis but kept as valuable reference sources. Eventually, there are 59 research papers considered relevant to construct the basis for the data synthesis. The above-mentioned collection process is presented in Appendix.

4. Results

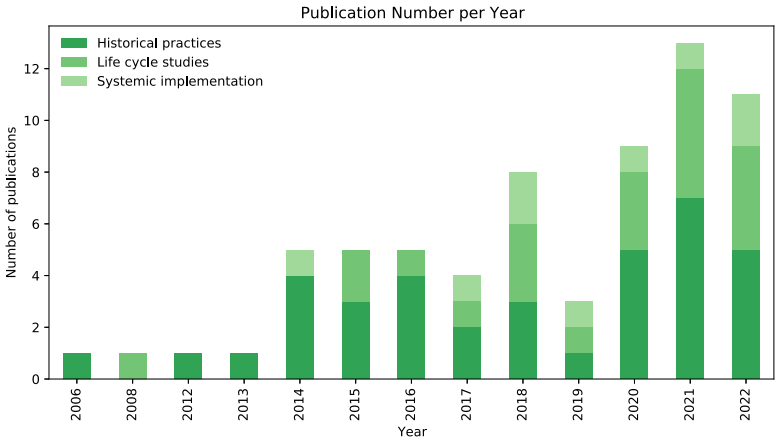
Corresponding to step 2 in the proposed methodology in Section 3, an overall summary will be given in this section of the collected literature including two main focuses: (1) a bibliometric analysis of publication numbers and geographical distribution; (2) a general content review of the articles regarding the concept of circular economy and their life cycle scope.

4.1. Descriptive analysis

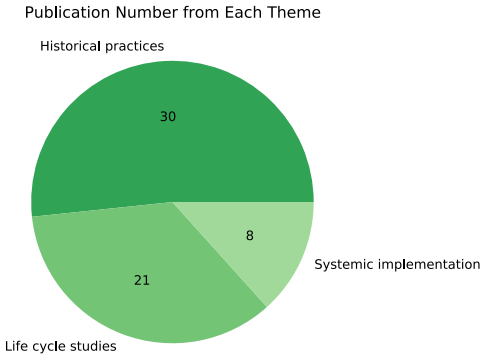
A brief descriptive analysis is conducted with statistical methods to grasp a general development trend of the topic, which will be presented from both spatial- and temporal aspects in the following part.

4.1.1. Publication numbers

Fig. 2(a) presents the number of publications that are collected in this review every year and Fig. 2(b) displays the total number of publications in each thematic category. Based on the historical overview in Section 2, the publications are categorized into three main themes: (1) investigating the technical performance of historical practices including recycling RAP and reusing other secondary materials into pavement



(a) Annual publication number per theme



(b) Total publication number per theme

Fig. 2. Summary of publication number.

construction and rehabilitation (30 studies); (2) assessing the cost and environmental aspects of recycling and reusing by applying life cycle studies (21 studies); (3) focusing on systemic implementation of circular economy through digitization (8 studies). To give a better comparison of the number of publications included per topic, they are marked by different colors in Fig. 2.

Overall, there is a significantly increasing number of studies contributing to this sustainability transition in the pavement sector; more importantly, the focuses of the publications have extended from limited to broader perspectives, engaging insights from different stakeholders. Fig. 2(a) and Fig. 2(b) indicate that the first theme has attracted the most research interest over the years as it offers the fundamental technical knowledge for achieving circular goals. It is worth noting hereby that even though the earliest collected study regarding RAP recycling is from 2006, the real history of it can be traced back to the 1970s when the petroleum crisis hit the binder market hard (Zaumanis et al., 2016). However, the earlier studies from the 80s and 90s are excluded during the material collection process in Section 3.1 mainly due to the lack of access or mismatching research focus. Meanwhile, since material recycling became a popular approach in asphalt production and use, LCA was also introduced to pavement engineering in the late 20th century to provide data-sound comparisons between the environmental impacts of traditional pavement construction methods and those of material recycling. In this review, the earliest LCA research that helps to understand the transition comes from 2008. Through the years, it is noticeable from Fig. 2(a) that LCA has gradually gained broad recognition in the field. Nowadays, it is a valuable tool for sustainability evaluation and informed decision-making processes. The last decade has witnessed the emergence of studies focusing on systemic implementation through digitization. The slow but steady growth, beginning in 2014, indicates a rising trend in integrating circular economy principles with digitization.

4.1.2. Geographical distribution

In Fig. 3, the worldwide distribution of studied cases in the pavement sector is depicted, with bubble size indicating the total number of studies from each country and colors representing different themes. As shown in Fig. 3, the circular economy discussions span the globe, with widespread recognition of the potential benefits of recycling and reusing observed across Africa, Asia, Europe, North America, and South America, excluding Oceania. China, the U.S., Italy, and Iran emerge as prominent contributors, with Italy and Iran emphasizing recycling and reusing, China showing significant attention to Life Cycle Assessment (LCA), and the U.S. demonstrating a balanced focus across themes, notably in systemic implementation. Besides, the Netherlands stands out with another two case studies within the same scope from different perspectives. One of the cases aims to identify the data requirements for building a pavement MP and eventually come up with a proposal for a potential MP; while the other one shares the importance of partnering to achieve the transition to CE in the infrastructure sector, based on a real-life road infrastructure case study InnovA58.

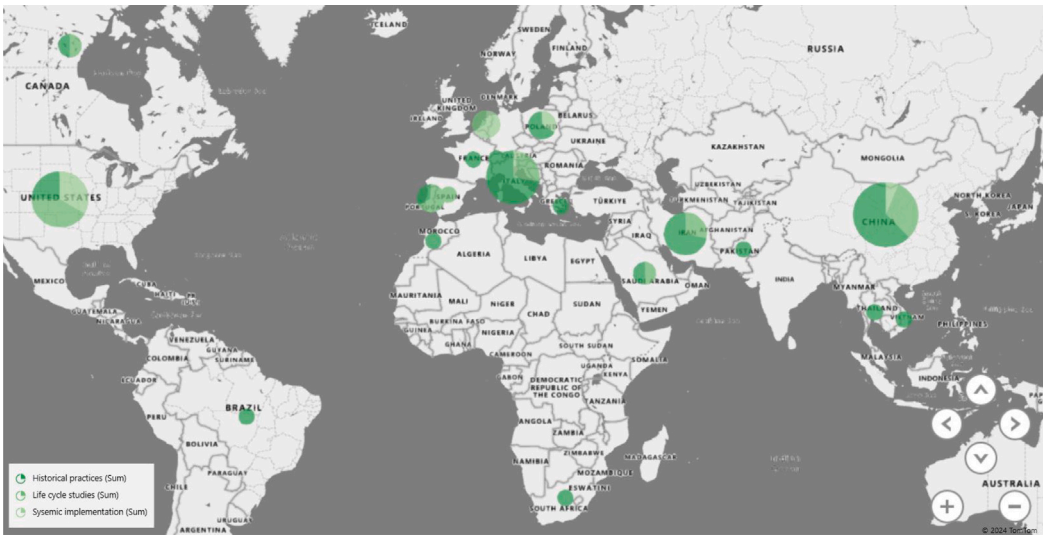


Fig. 3. Geographical distribution of the collected publications.

4.2. Content analysis

The descriptive analysis has indicated the overall development direction while further content-based analysis is still needed. The following content analysis is conducted to give a more general picture of the transition from a methodological point of view such as the definition and the system boundary.

4.2.1. Definition of circular economy in pavement engineering

As one of the core values of the future transition in pavement engineering, the circular economy has been mentioned extensively in the existing literature. Yet explicit definitions of circular economy are seldom given by researchers. Among all the included studies, there are only 5 publications that have defined this term in the authors' own words or by referring to other authorities (Anwar et al., 2021; Mantalovas et al., 2020; Rangelov et al., 2022; Zande, 2022; Vlaming, 2018).

Anwar et al. (2021)'s study is the only one that has given an unequivocal description of the circular economy on its own. They have specified the circular economy as "*a model that has the potential to transform, preserve and reallocate materials, items, and goods back into the economy in an optimal way using as much as it is ecologically, functionally, socially, and cost effective*".

The most cited definition comes from Ellen MacArthur Foundation (2013), in which they have depicted the circular economy as "*economy that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.*" Established in 2010, Ellen MacArthur Foundation has been expanding the awareness of the circular economy (Stahel, 2016) and delivering structured toolkits for policymakers (Ellen MacArthur Foundation, 2015).

Simultaneously, Kirchherr et al. (2017)'s work is another commonly cited source when researchers introduce the development of the concept. Based on a review of 114 definitions that appeared in earlier work, they have concluded the circular economy is "*an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes*". The authors have also criticized the way of understanding and promoting circular economy as "*"a bit of twisting of the status quo"*" with minimal reform on the current business model (e.g. claiming to be part of the circular economy by only increasing recycling rate).

Despite the popularity of these two sources, they only provide a generalized definition of the circular economy at a macro level. How should the circular economy be adapted in the pavement sector is, however, left without a consensus. Exactly with such a research question, Mantalovas et al. (2020) have conducted a questionnaire survey of several national road authorities of 9 European countries on their understandings of the circular economy and how they implement it. The road authorities' answers revealed that the circular economy is often operationalized as encouraging asphalt recycling, replacing conventional materials with secondary ones, and applying preventive maintenance. At the same time, the national road authorities have commonly admitted the hindrances they experienced due to the lack of clear legislation support and incentives. In most of the surveyed countries, the circular economy often appears as a guiding concept in their national development scheme where material banks and material passports, along with material flow tracking are proposed and a change in business patterns that supports innovation and partnering is encouraged. Nonetheless, there are no clear roadmaps or strategic plans to assist the transition to a circular economy for road infrastructure, which has resulted in the lack of common ground to engage more stakeholders. Essentially, this absence of a clear definition of the circular economy in pavement engineering has reflected the challenges and dilemmas in the holistic implementation of the circular economy in the pavement sector.

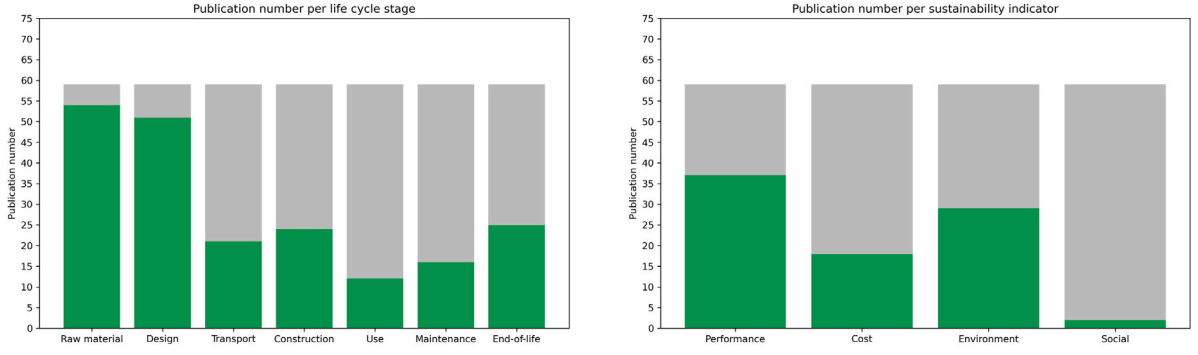
4.2.2. Circular economy practices by life cycle stages

Table 1 briefly compares the life cycle system boundaries of the collected studies and the sustainability metrics (performance, cost, and environment) that have been covered. The division of pavement life cycle phases follows the recommendation by Harvey et al. (2016) in the Federal Highway Administration report, including raw material extraction & production, design, transportation, construction, use, maintenance & rehabilitation, end-of-life stages. Based on the summarized results in Fig. 4(a), most research works have included the raw material extraction & production stage and design stage while the rest of the life cycle stages tend to be omitted for different reasons. In accordance with the scholars' focused interests in the material-related stages, the mechanical performance of the pavement materials has also been broadly evaluated in the existing studies.

One of the biggest shortcomings in most studies stems from the missing transportation component as the sustainable advantages of pavement recycling practices are highly influenced by haul distance (Turk et al., 2016; Santos et al., 2017). Based on the sensitivity analysis

Table 1
Coverage of pavement life cycle stages and sustainability indicators in the publications.

Author (Year)	Life Cycle Stages							Sustainability Evaluation		
	Raw material extraction & production	Design	Transportation	Construction	Use	Maintenance & Rehabilitation	End-of-life	Performance	Cost	Environment
Loizos and Papavasiliou (2006)	Yes				Yes	Yes				
Alkins et al. (2008)	Yes	Yes						Yes	Yes	Yes
Hugener et al. (2014)	Yes			Yes			Yes			
Praticò et al. (2013)	Yes						Yes	Yes		
Dal Ben and Jenkins (2014)	Yes	Yes				Yes	Yes	Yes		
Modarres et al. (2014)	Yes	Yes				Yes		Yes		
Yousefi et al. (2021)	Yes	Yes				Yes		Yes		
Gao et al. (2014)	Yes							Yes		
Mallick et al. (2014)	Yes	Yes	Yes	Yes		Yes	Yes (Aggregates)	Yes	Yes	Yes
Diefenderfer et al. (2015)					Yes			Yes		
Zanetti et al. (2015)	Yes	Yes					Yes (Tire)	Yes		
Giani et al. (2015)	Yes	Yes	Yes	Yes		Yes	Yes			Yes
Sangiorgi et al. (2015)	Yes	Yes		Yes			Yes (CDW)	Yes		
Santos et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes			Yes
Presti et al. (2016)	Yes	Yes						Yes		
Magnoni et al. (2016)		Yes		Yes		Yes		Yes		Yes
Turk et al. (2016)	Yes	Yes	Yes	Yes						Yes
Stimilli et al. (2017)	Yes	Yes						Yes		Yes
Kasmi et al. (2017)	Yes	Yes						Yes		Yes
Santos et al. (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes
Wang et al. (2018)	Yes	Yes						Yes		
Li et al. (2018)	Yes	Yes						Yes		
Eskandarsefat et al. (2018)	Yes	Yes			Yes		Yes (Tire)	Yes		
Chen and Wang (2018)	Yes	Yes	Yes	Yes				Yes		Yes
Yu et al. (2018)	Yes	Yes	Yes	Yes						Yes
Subedi et al. (2018)	Yes	Yes	Yes						Yes	Yes
Vlaming (2018)										
Cao et al. (2019a)	Yes	Yes	Yes	Yes			Yes		Yes	Yes
Cao et al. (2019b)	Yes	Yes			Yes	Yes		Yes	Yes	
Ingrassia et al. (2020)	Yes	Yes				Yes		Yes		
Rudnicki and Jurczak (2020)	Yes					Yes		Yes		
Wang et al. (2020)	Yes	Yes					Yes (Tire)		Yes	Yes
Amrani et al. (2020)	Yes	Yes					Yes (PG)	Yes		Yes
Jahanbakhsh et al. (2020)	Yes	Yes		Yes				Yes	Yes	Yes
Zarrinkamar and Modarres (2020)	Yes	Yes	Yes	Yes				Yes	Yes	Yes
Yu et al. (2020)	Yes	Yes	Yes	Yes				Yes	Yes	Yes
Mantalovas et al. (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pan et al. (2021)					Yes	Yes		Yes		
Taherkhani and Noorian (2021)	Yes	Yes						Yes		
Xu et al. (2021)	Yes	Yes					Yes (Tire & Plastic)	Yes		
Kabir et al. (2021)	Yes	Yes					Yes (Plastic)			
Anwar et al. (2021)	Yes	Yes					Yes (Plastic)	Yes		
Santos et al. (2021)		Yes								Yes
Zhang et al. (2021)	Yes	Yes	Yes	Yes						Yes
Ruffino et al. (2021)	Yes	Yes	Yes						Yes	Yes
Offenbacker et al. (2021)	Yes	Yes	Yes						Yes	Yes
Mattinzioli et al. (2021)	Yes	Yes	Yes	Yes					Yes	Yes
Rangelov et al. (2021)	Yes	Yes	Yes	Yes	Yes	Yes	Yes			Yes
Benjeddou and Mashaan (2022)	Yes	Yes					Yes (Marble)	Yes		
Calandra et al. (2022)	Yes	Yes					Yes (Mining industry)	Yes		
Liu et al. (2022b)	Yes	Yes	Yes	Yes			Yes (PG)	Yes	Yes	Yes
Carmo et al. (2022)	Yes	Yes					Yes (CDW)	Yes		
Li et al. (2022)	Yes	Yes					Yes (Circuit board)	Yes		
Yao et al. (2022)	Yes	Yes	Yes	Yes			Yes		Yes	Yes
Ma et al. (2023)	Yes	Yes						Yes	Yes	
Alharbi et al. (2022)	Yes	Yes		Yes					Yes	
Amarh et al. (2022)	Yes	Yes	Yes	Yes	Yes					Yes
Rangelov et al. (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes			Yes
Zande (2022)	Yes	Yes		Yes				Yes		



(a) Number of publications per life cycle stage

(b) Number of publications per sustainability indicator

Fig. 4. Summary of publication numbers regarding life cycle stages and sustainability indicators.

conducted on a case study in Sweden, Miliutenko et al. (2013) concluded that by extending the transport distance of RAP from 20 km to 50 km, the energy savings of hot in-place recycling will increase significantly while that of hot in-plant recycling will show a sharp decrease. Regarding the construction stage, it is usually overlooked in the studies in theme 1, as a considerable amount of the research work is only conducted in laboratories without a real-life case study. In contrast, energy consumption and GHG emissions during construction phases are present in a large percentage of the life cycle studies, especially the ones that compare recycling and reusing practices with traditional paving. These comparative studies provide valuable insights into the long-term environmental and economic benefits of shifting from traditional construction and reconstruction with virgin materials to applying RAP and other secondary materials. Among all the stages, the use stage has been covered by the least number of studies. It is worth clarifying that the use stage does not represent the total environmental impacts and costs related to the traffic. Instead, it accounts for the marginal vehicle operation costs and environmental impacts incurred by pavement–vehicle interaction as a consequence of pavement condition deterioration (Santos et al., 2015). However, the limited in-service pavement systems that are built with recycling and reusing techniques have made it impossible to predict pavement behaviors and deterioration trends. Thus, the lack of field data gives no ground for the assessment of use stages to stand on. Another issue that could be identified in Fig. 4 and Table 1 is the exclusion of the end-of-life stage. Most publications leave the circularity of pavement materials containing novel elements uncertain, with few addressing ecotoxicity risks through leaching tests (Kasmi et al., 2017; Amrani et al., 2020; Liu et al., 2022b). In a laboratory study of recycling phosphogypsum as a base course material by Amrani et al. (2020), significant leakage of Zinc exceeding the Environment Protection Agency (of the U.S.) threshold can be observed after the leaching tests, bringing ecological concerns to soil and underground water.

Fig. 4(b) compares the number of publications per sustainability indicator. Even though considerable portions of the literature covered performance and environmental indicators, most of the studies that considered the performance aspect did not overlap with the studies that considered the environment aspect, which could be drawn from Table 1. Besides, it is also worth noting that two studies have included the social aspect in their evaluation framework (Alkins et al., 2008; Alharbi et al., 2022). Alkins et al. (2008) discussed the social benefits of cold in-situ recycling such as minimizing disruption to motorists and residents nearby. Alharbi et al. (2022) took a step further by incorporating the social metric into a fuzzy analytic hierarchy process, howbeit their work focused on the difficulty of constructing with cold in-situ recycling for the personnel and the need for advanced equipment.

In addition, the coverage of life-cycle stages has reflected the limited engagement of stakeholders in the circular transition process. Dominance in the initial material production and pavement construction stages indicates a focus on asphalt manufacturers' and road contractors' interests. Meanwhile, the emphasis on the mechanical performance of current practices addresses the main concerns of road agencies. On the other hand, the lack of policy incentives and technical guidance has incurred a limited number of in-service pavements with novel materials and consequential data accessibility issues (Wang et al., 2020). The role of road users and the public that are influenced by the environment and eco-systems, thus, remains anonymous in the decision-making system.

This list in Table 1 gives a general overview of the circular economy development in the pavement sector, which can serve as a compass for the identification of research gaps in the following sections.

5. Discussions

Based on the previous analysis, the literature is further evaluated to find the research boosters and gaps to answer the proposed research questions. Due to the heterogeneity of the included work, different dimensions are designed and applied in Section 5.1, Section 5.2, and Section 5.3. Additionally, as the last step in the proposed methodology, Section 5.4 presents the summarized results based on previous quantitative analysis and evaluation categories.

5.1. Historical practices

In the following section, the discussion is focused on the above-mentioned historical practices. The included work is summarized and analyzed through multiple perspectives. The studies in theme 1 are clustered into two sub-themes: recycling pavement materials and reusing waste materials in pavements, corresponding to Section 2.1. In accordance with the research interests of this review, the overall technical aspects of the presented practices are reviewed separately due to the differences in recycling pavement and reusing secondary materials. However, in spite of the perspectives of practice quality control, sustainability performance, and policy support, the subtle nuance between these two sub-themes has made it possible to conduct an analysis in parallel and grasp a better picture of the industry.

5.1.1. Pavement material recycling

The collected pavement material recycling research consists of 16 journal articles. Even though neither "asphalt" nor "concrete" has been used as a keyword filter during the database search process, one of the most prominent features is their interest in asphalt pavement compared to concrete pavement except for two articles focusing on recycling concrete pavement as aggregates. Based on a case study for airport pavement rehabilitation, Magnoni et al. (2016) presented a performance and environmental assessment of in-situ recycling of concrete pavement as base and subbase cement bounded layers for reconstructing new asphalt pavements. The heavy loads of aircraft on the taxiway and limited downtime for maintenance and rehabilitation have brought extra challenges to the case study. On the basis of accomplishing the technical demands for airport taxiways, the recycled aggregates have also achieved a great reduction in carbon emissions from hauling impacts and material production. In another case project, Rudnicki and Jurczak (2020) conducted a mechanical investigation on the recycled aggregates from a concrete pavement that was under 82-year heavy traffic condition loading. The test results showed that these aggregates could meet the highest quality requirements for the extra heavy-duty pavements according to European Standards. Both studies have indicated the feasibility of recycling concrete slabs as aggregates for new pavement construction. The result from the presented preliminary carbon footprint assessment by Magnoni et al. (2016) has also implied the possible environmental benefits of streamlined recycling.

Among the other 14 studies on asphalt recycling, there are 3 papers focusing on traditional recycling with hot mix asphalt (HMA). The pavement industry has, however, been encouraged by many researchers and responsible road authorities to engage in more environmental-friendly alternatives. Warm recycling, which requires the asphalt to be produced and applied at 20–40 °C lower than that of hot recycling, has received a considerable amount of attention (Kheradmand et al., 2014). Two lab investigations on recycling with warm mix asphalt technology are presented by Stimilli et al. (2017) and Yousefi et al. (2021), respectively. Besides, there is no doubt that the cold recycling technique has induced the most discussions over the last two decades, especially the use of cold in-place recycling (CIR or CIPR, referred to as CIR in the rest of the article). The use of CIR technique dates back to the 90s with the advances in cold recycling equipment (Loizos and Papavasiliou, 2006). The significant advantages of CIR include and are not limited to (1) reduction in costs and carbon footprints that are related to haulage and virgin aggregates production; (2) decrease in energy consumption and carbon emission from heating in comparison to hot recycling; (3) less construction time and lower traffic disruption due to work zone control (Jenkins, 2000; Hugener et al., 2014). However, even though there has been a boost in the research on CIR mixture

design, the implementation of cold recycling in practice is still heavily restricted owing to several factors. Besides the high costs for bitumen emulsion and paving equipment, some of the most fundamental reasons are believed to be the inferior mechanical performance of cold recycled mixtures in comparison to conventional materials and the lack of standardized design methods that are internationally accepted (Modarres et al., 2014). With respect to a systemic view, the uncertainties from its technical performance bring extra interest to life cycle studies in the long run.

After determining the recycling technique to be applied, the future whereabouts of the recycled pavement materials are another key point. Some of the collected literature (6 out of 16 articles) is deliberated on lab investigation of the mechanical performance of the recycled asphalt mixture. In general, these studies aim to evaluate the influence of different dosages of RAP and other recycling agents. Several projects have assessed the empirical and mechanical performance of applying RAP in the wearing course with both lab experiments and field investigations, albeit more case studies have chosen to adopt RAP and recycled concrete aggregates into the base course or sub-base course. A possible explanation could be the vague specifications or restrictions from local transportation departments. Rudnicki and Jurczak (2020) addressed in their case project that the investigated reclaimed material could have been used for paving the surface layers, which was unfortunately not supported by guidelines and specifications in Poland.

Due to similar reasons, it has also been a long struggle to achieve more widespread use of asphalt with a higher percentage of RAP (Presti et al., 2016). A decade ago, the RAP content in real-life projects was typically less than 15% because there was no requirement for additional tests for such a percentage. The evolving emphasis on sustainable infrastructure, stricter environmental regulations, and changing materials market are serving as incentives for the road sector to reconsider the economic and environmental gains of allowing higher RAP content during paving without sacrificing the quality of the pavement system (Copeland et al., 2011). Among the collected work, several studies have shed light on the feasibility of increasing RAP percentages in wearing courses and other pavement layers. For example, Dal Ben and Jenkins (2014), Yousefi et al. (2021), and Taherkhani and Noorian (2021) have evaluated the mechanical performance of the asphalt mixtures with different RAP percentages based on lab experiments. Their results revealed that besides the content of RAP, the performance of the mixtures was heavily affected by a series of other mixed factors such as temperature, mixing time, the recycled material source, type, and dosage of the recycling agent and virgin binder. Meanwhile, there is another trend in reaching RAP content that is from 50% to even 100% in combination with the assistance of different recycling agents and additives. It is noticeable that the 100% recycling rate is usually achieved by downgrading the materials into sub-base courses or with cold in-place recycling.

In order to obtain asphalt mixtures of satisfying quality, the common practice is to add various modifiers and recycling additives into the mixture depending on its original properties. To maximize RAP usage, the reviewed articles have covered a wide variety of modifiers and additives. Due to the divergent condition of investigated RAP materials in each study, it becomes a tactical task to come up with a general mixture design guide, especially considering the lack of comprehensive understanding of the mechanisms involved in mixing asphalt and uncertainties on mixtures final performance (Presti et al., 2016). Thus, it is widely recognized by pavement engineers that to ensure the desired long-term performance of high RAP content pavement, the current mixture design and test methods have to be adapted to guide the selection of recycling agents regarding the type, the appropriate dosage, and blending techniques. Another concern arises from the lack of knowledge about the recyclability of pavement materials containing recycling agents. From a long-term perspective, it is of vital importance to ensure that the modifiers and additives can be 100% recycled at the end of their life cycle and will not impact the recyclability of the rest of the pavement materials (Ingrassia et al., 2020). Such considerations have left a research gap that cannot be overlooked for systemic sustainability effectiveness evaluation of the recycling practice. However, among all the reviewed work within the theme, only Ingrassia et al. (2020) raised their apprehension in spite of the recycling potential of the bio-binders (by-products of the paper and wood industries) that were mixed with RAP.

5.1.2. Waste material in pavement production and construction

Besides the studies on pavement material recycling, there are another 14 articles included in theme 1, but on the usage of other waste materials for pavement production instead. It is worth noting that there is 1 case study by Taherkhani and Noorian (2021) included in both categories as it investigates the performance of RAP and waste cooking oil at the same time. The following Table 2 displays the types of external materials that have been employed and their corresponding function in the process of pavement production and construction. According to Table 2, it is obvious that most of the assessed waste materials have been used either for asphalt modification or subbase and foundation layers construction after treatment.

As asphalt additives

Since the 1970s, there has been a rapid growth in polymer modifier research because of its promising effects on increasing stiffness at high temperatures, decreasing crack resistance at low temperatures, improving moisture resistance, and prolonging fatigue life of the asphalt mixture (Tayfur et al., 2007; Zhu et al., 2014; Wu et al., 2024). On the other hand, the inclusion of modifiers during asphalt production could raise the cost by up to 40% (Yildirim, 2007) and cost-effectiveness is always a huge driving force for infrastructure planning. Thus, pavement engineers have been actively looking for more economic alternatives to replace virgin polymers. In this review, CR from waste tires presents as the most popular external material for polymer modification. Besides the investigations on its modification functionality, more studies have also put efforts into characterizing the compatibility of CR with other reclaimed materials such as RAP (Eskandarsefat et al., 2018) and PET modifiers (Xu et al., 2021). In addition to traditional laboratory mechanical performance tests, Eskandarsefat et al. (2018) have also conducted functional field tests to attain measurements on macro texture, micro texture, and acoustic properties of the pavement containing CR. In comparison to mechanical evaluation, these indexes could outline the field performance better from the road users' perspectives. Despite all the advantages of applying CR, it has also been addressed by several existing studies that CR from different sources and treatments have a considerable influence on the final performance of the mixture. The impurities in CR could impede the homogeneity of the modified binder and initiate damages (Zanetti et al., 2014). Furthermore, these foreign elements and other organic substances such as volatile organic compounds and polycyclic aromatic hydrocarbons are certain factors to consider for the sake of the environment. In consequence, chemical analyses (such as Toxicity Characteristic Leaching Procedure tests to examine the content of metals) are recommended for a comprehensive assessment of CR and modified mixtures.

Apart from the material science aspect, another well-recognized reason for incorporating CR into asphalt production is because of the daunting challenge of recycling waste tires worldwide. Globally approximately 1.5 billion tires are being wasted after usage every year. Moreover, the problem is still growing and the annual number of global waste tires is expected to reach up to 5 billion by the year 2030. However, the existing studies have focused primarily on the technical performance and mechanical properties of CR in asphalt mixtures, or its related energy reduction and cost savings (Dobrotă and Dobrotă, 2018) while leaving the quantification of CR demands and the logistics behind it barely touched. Wang et al. (2020) led a pioneering case project in China to demonstrate a prediction model to simulate the supply of waste tires and the corresponding demand for these tires in three road construction scenarios for 5 years. They have

Table 2
Summary of external secondary materials in pavement production and construction.

Recycled as	Secondary material type	Number of publications	Author(year)
Asphalt modifier	Crumb rubber (CR)	4	Sangiorgi et al. (2015), Zanetti et al. (2015), Wang et al. (2020), Xu et al. (2021)
	Plastic packages (thermoplastics)	3	Anwar et al. (2021), Kabir et al. (2021), Xu et al. (2021)
	Non-metallic powder from e-waste (cured epoxy resin and glass fiber)	1	Li et al. (2022)
Asphalt filler	Manganese ore tailing	1	Calandra et al. (2022)
Asphalt rejuvenator	Waste cooking oil	1	Taherkhani and Noorian (2021)
Embankment and foundation layers	Construction and demolition waste (CDW)	2	Sangiorgi et al. (2015), Carmo et al. (2022)
	Phosphogypsum	2	Amrani et al. (2020), Liu et al. (2022b)
	Marble waste	1	Benjeddou and Mashaan (2022)
	River sediments	1	Kasmi et al. (2017)

also appended a comparative cost and energy analysis on the proposed CR-modified mixture and one other mixture with a virgin modifier. This predictive assessment has indicated the huge demand potential for CR in road construction and its prospects for energy savings and emissions reduction in the long run.

As presented in Table 2, Polyethylene terephthalate (PET) from commodity plastic packages is another popular alternative for asphalt modification, addressing environmental concerns about plastic waste with its production increasing exponentially from 1.5 million tonnes in 1950 to 359 million tonnes in 2018 (European Parliament, 2023). The application of PET in pavement, similar to CR, dates back to the '90s. While a wide range of studies show performance improvements in rutting and fatigue resistance due to the introduction of waste plastics, inconsistent results exist due to factors like insufficient mixing conditions and poor temperature controls (Heydari et al., 2021). In this review, three lab-based projects have highlighted different perspectives on secondary plastic reuse. Anwar et al. (2021) compared the results of Marshall stability tests on the modified samples containing PET from plastic bottles and polyethylene (PE) from gas pipes at different percentage levels. In their tests, the PE-based mixture had better strength properties than the PET-based mixture, which has drawn emphasis on the importance of material selection to accomplish the optimum circular effectiveness of secondary materials. Kabir et al. (2021) and Xu et al. (2021) have analyzed the compatibility of PET with other waste materials (vegetable-based waste cooking oil and CR). Besides traditional mechanical tests, physical–chemical tests are also included in both studies to gain a more thorough understanding of the mixtures. All three assessments done independently have confirmed the positive effects of PET on the mixtures from multiple aspects.

Beyond thermoplastics, efforts to enhance asphalt include thermosetting plastics and non-organic materials. Li et al. (2022) discussed the possibility of utilizing the non-metallic power from printed circuit boards, which contained two main components: cured epoxy resins and glass fiber. Overall a promising improvement in the asphalt properties could be noticed, which also aligns with other preceding studies on e-waste recycling in pavement production (Hasan et al., 2016).

At the same time, virgin modifiers are not the only type of asphalt additive that has been replaced with novel waste material options. Included in the previous section, Taherkhani and Noorian (2021)'s work used vegetable-based waste cooking oil to rejuvenate asphalt mixtures containing low to high RAP contents. The laboratory results have confirmed the effects of the applied waste cooking oil as a rejuvenator and its optimum dosage in accordance with different RAP percentages. Fillers are another important asphalt additive that is introduced to reduce the flow of particles within bitumen and to enhance the resilient modulus of the mixture (Calandra et al., 2022). Instead of adding the traditional fillers such as cement, lime, limestone, and stone dust, alternatively, Calandra et al. (2022) gave an example of using tailings from manganese ore as asphalt fillers which consisted of oxides of Al, Si, Mn, and Fe.

Into foundation layers

The pavement foundation layers play an essential structural role in road construction, with the subbase layer facilitating traffic loading distribution. Traditional subbase layers use granular or cement bound materials. Included in this review, river sediments (Kasmi et al., 2017) and phosphogypsum from phosphate ores (Liu et al., 2022b) have been suggested as paving options for subbase layers.

The management of river sediments from dredging is becoming a complicated issue as the regulations on dumping are tightening up. With the 50 million m^3 sediments generated each year in France, which constitutes almost 1/10 of the global total amount, Kasmi et al. (2017) proposed to add a second life for the dredging sediments as a new source of subbase materials. Due to the novelty of the waste material, the authors included a characterization study covering its physical–chemical, mechanical, and geotechnical properties with leaching tests to quantify its ecological toxicity. Due to several reasons like water content, organic matter content, and grain size distribution, the bearing capacity of the sediment failed to meet the standard for the subbase layer at both laboratory and field scales.

Liu et al. (2022b), instead, considered phosphogypsum for potential subbase material, a by-product of the phosphorous fertilizer industry. Similarly to other waste materials, the annual production of phosphogypsum worldwide is drastically increasing, leading to severe environmental and social concerns. A popular method of introducing phosphogypsum in pavement foundation layers is to apply it as an additive, which means the phosphogypsum has to be combined with other stabilizers such as cement to stabilize the soil or the crushed stone (Liu et al., 2022b). The issue with this method is that the different properties of soil and crushed stone from different sources could induce uncertainties in the final mixture with phosphogypsum, requiring case-specific investigations. To overcome such potential risks, Liu et al. (2022b) explored the feasibility of completely replacing the soil and crushed stone with calcined phosphogypsum while still keeping the untreated phosphogypsum as a filler. As a pilot study, this article has given a more general sustainability performance of the proposed attempt from technical, cost, and environmental perspectives. The positive preliminary results have confirmed the value of further investigation.

With the same apprehension related to accumulating phosphogypsum, Amrani et al. (2020) found untreated phosphogypsum unsuitable for embankment based on the chemical and mineralogical tests. On the contrary, Sangiorgi et al. (2015) proposed using construction and

Table 3
Summary of the evaluated practices in life cycle studies.

Evaluated practice	Number of publications	Author(year)
CIR	9	Alkins et al. (2008), Santos et al. (2015), Giani et al. (2015), Turk et al. (2016), Santos et al. (2017), Zarrinkamar and Modarres (2020), Offenbacker et al. (2021), Alharbi et al. (2022), Amarh et al. (2022)
HIR	4	Yu et al. (2018), Cao et al. (2019a), Yu et al. (2020), Ma et al. (2023)
RAP	5	Chen and Wang (2018), Zarrinkamar and Modarres (2020), Mattinzioli et al. (2021), Jahanbakhsh et al. (2020), Yao et al. (2022)
CR	1	Mattinzioli et al. (2021)
Paint sludge	1	Ruffino et al. (2021)
Plastic	2	Santos et al. (2021), Yao et al. (2022)
Geopolymer	1	Zhang et al. (2021)

demolition waste (CDW) for embankment, later supported by Carmo et al. (2022) for permeable pavement. Apart from CDW, the depletion of natural aggregates and its related secondary effects like erosion and deforestation have encouraged researchers to look for more possible substitute materials. In this context, Benjeddou and Mashaan (2022) exemplified the usage of marble waste from marble cutting and polishing as aggregates, reflecting a potential market for marble waste in road construction and a possible solution to its related ecological problem.

5.2. Sustainability evaluation with the developing life cycle principle

The 21 studies from theme 2 are established on a life cycle framework. As mentioned in earlier sections, LCA and LCCA have been commonly regarded as efficient tools to evaluate the circularity of a certain product or process. With the extensive amount of performance research and technical investigations on all types of recycling and reusing practices within the pavement industry, there are still several steps left until full-scale implementations in real-life projects. A more comprehensive understanding of the sustainable benefits of the booming variety of novel alternatives is one of the missing elements. Table 3 displays the categories of practices that have been evaluated in the review articles, offering a brief summary of the research trend within theme 2.

As one of the most popular recycling options, Hot In-place Recycling (HIR) has received a fair amount of in-depth investigation from different perspectives over the years. Yu et al. (2018) integrated a discrete event simulation model with LCA to address the uncertainties related to the HIR process and transportation stage of the LCA framework, on the basis of which, they (2020) engaged the cost and performance functions to conduct a multi-objective optimization model. Without focusing on the performance function, an Eco-Efficiency Analysis method was introduced by Cao et al. (2019a) to combine LCA and LCCA of HIR.

As presented in Table 3, CIR has gained the most attention within the topic, which exactly corresponds to the discussions in Section 5.1.1. The interesting thing here is that CIR has collectively received considerable research emphasis in spite of the technical, cost, and environmental aspects. It is reasonable to anticipate more popular usage of CIR and policy support with the provided evidence worldwide. Many studies have confirmed that the CIR technique results in a significant reduction in GHG emissions and energy consumption in comparison to traditional reconstruction or recycling in plants (Giani et al., 2015; Turk et al., 2016). Notwithstanding, it has also been marked by Giani et al. (2015) that the reduction of environmental impacts in CIR is mainly saved by the limited hauling effects, which would be diluted over time. Thus, in order to reach improved environmental benefits in the long run, researchers have suggested the incorporation of CIR with RAP and other secondary materials such as using pozzolanic waste as fillers (Zarrinkamar and Modarres, 2020).

Apart from being combined with CIR, the life cycle impacts of RAP have also been assessed either in the conventional application case with HMA (e.g. Chen and Wang (2018)) or in the cases where other environmental-friendly methods or secondary materials are also involved to improve the overall sustainability of the mixtures reciprocally (e.g. with PET modifier (Yao et al., 2022), with CR and warm mix and half-mix technology (Mattinzioli et al., 2021)).

Additionally, it is worth noting that a wide variety of alternatives to primary pavement materials has been included in recent years, such as paint sludge (Ruffino et al., 2021), plastic waste as modifier or aggregates (Santos et al., 2021; Yao et al., 2022), and geopolymer (Zhang et al., 2021) even though not all the attempts turned out to be an optimal replacement for virgin materials. For example, in the case study of applying geopolymer in road base layers, Zhang et al. (2021) concluded that in contrast to the reduced global warming potential, all the other 10 environmental impact indicators were worsened compared with conventional road bases. These negative results have particularly reflected the importance of comprehensive environmental impact assessment during the promotion of circular economy practices in pavement engineering. Furthermore, the lack of a combination of LCA/LCCA evaluations with mechanical investigations of the alternatives in current studies leads to concerns about the durability and useful lifetime of the materials. There are possibilities of a "sustainable" mixture incorporating RAP, waste materials are accompanied by a demand for more frequent maintenance, which would result in increased construction sites on the network and thus increased risk of accidents and inconvenience for the users.

Uncertainties behind the life cycle studies

In an ideal case, a life cycle study involves cradle-to-grave assessment, demanding excessive demand for data acquisition. For LCCA, costs are universally evaluated in monetary terms, whereas LCA for environmental evaluation considers various impact metrics. As recommended by US EPA (2006), the three prime environmental impact categories include (1) human health, (2) ecological health, and (3) resource depletion, which can be further broken down into several normalized metrics such as global warming potential, acidification potential, eutrophication potential, and land availability. There exist a few Life Cycle Inventory Assessment (LCIA) methodologies that have been applied in the pavement sector, including CML (Guinée, 2002), ReCiPe (Goedkoop et al., 2009), TRACI (Bare, 2011). Table 4 summarizes the data sources of life cycle inventories in the reviewed publications and the corresponding impact metrics that have been included.

It is easily noticeable that the existing life cycle research tends to apply mixed sources of data due to the limited availability of relevant data and information. Besides the commercial databases and other open-source databases that are based on an average value, many reviewed LCA/LCCA work chose to incorporate data from previous literature

Table 4
Data sources of life cycle inventories and included impact indicators in the publications.

Author	Data sources	Impact metrics
Alkins et al. (2008)	PaLATE	GHG emissions
Giani et al. (2015)	Local organization, Ecoinvent, previous literature	Greenhouse Gas Protocol, ReCiPe 2008, Cumulative Energy Demand, Water Use
Santos et al. (2015)	Local transportation department, LCA inventories, previous literature	Climate change, acidification, eutrophication, human health criteria pollutants, photochemical smog formation and abiotic resource depletion
Turk et al. (2016)	Gabi 4.0, LCI, previous literature, EPD	Global Warming Potential, Acidification, Abiotic Depletion
Santos et al. (2017)	Previous literature, local DOT, suppliers and dealers	N/A
Chen and Wang (2018)	Online databases, previous literature	GHG emissions
Yu et al. (2018)	NONROAD model	CO2 emissions
Cao et al. (2019a)	Not mentioned	Raw material consumption, energy consumption, emissions, toxicity potential, and risk potential
Jahanbakhsh et al. (2020)	Previous literature	CO2 emissions, energy consumption
Zarrinkamar and Modarres (2020)	Not mentioned	Toxicity leaching characteristics, energy usage and CO2 emissions
Yu et al. (2020)	NONROAD model	Global warming potential, acidification potential and respiratory effects potential, as well as energy consumption
Santos et al. (2021)	Suppliers and dealers, DOT, online surveys	Climate change, acidification, eutrophication, ozone layer depletion and photochemical oxidation
Zhang et al. (2021)	Ecoinvent 3, previous literature, local specifications	Abiotic depletion, abiotic depletion-fossil fuels, global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication
Ruffino et al. (2021)	Eurobitume, local supplier, Ecoinvent,	Global warming potential, gross energy requirement
Offenbacker et al. (2021)	Previous literature	N/A
Mattinzioli et al. (2021)	Suppliers and dealers, DOT, previous literature	GHG emissions
Yao et al. (2022)	Governmental reports, specifications, public/commercial databases, open-source software tools, literature, and a survey of equipment information	Global warming potential
Ma et al. (2023)	Not mentioned	N/A
Alharbi et al. (2022)	Local DOT	N/A
Amarh et al. (2022)	PySuPave (LCA tool by Virginia DOT)	Global warming potential

despite the geographical and economic discrepancies. The reliance on prior literature can lead to a snowball effect, potentially culminating in a non-negligible deviation from the actual case. Moreover, several studies have indicated the sensitivity of the final impact results over certain inventory values (Giani et al., 2015; Turk et al., 2016). Thus, the accuracy of the assessment outcomes is critically dependent on the referred work and the context of the case.

In reporting impact indicators, no unified guideline is evident in literature. While some studies choose emissions and energy consumption, others prefer normalized impact categories for decision-makers' reference. One of the significant advantages of using normalized metrics is that they translate numbers into quantified impacts on the different parts of ecosystems, which can provide more straightforward reference information for decision-makers. Table 4 implies the pavement researchers' preferences towards the CML methodology, which has been widely used in the construction sector (Khasreen et al., 2009). Another noteworthy thing is the application of EPD data by Turk et al. (2016) which indicates the potential of EPD in offering verified and traceable data for LCIA. Unfortunately, it seems like EPD is still seldom utilized, probably owing to its limited data repository and lack of incentives. In addition, as mentioned in earlier sections, it is difficult to deny that one of the main initiatives for reusing waste materials in pavement production and construction is the stricter policies and land scarcity for disposal and landfill. Notably, land-use-related indicators,

Table 5
Summary of the early studies aiming to achieve systemic upgrade.

Author (year)	Focus	Method/Tool	Engaged stakeholders
Mallick et al. (2014)	Aggregate stocks and their influence on haul distances	System dynamic modeling	Road agencies, policy makers, road contractors, society
Subedi et al. (2018)	Development of a decision-making aid tool for choosing mix design based on EPD and agency cost	Case study	Material manufacturers, road contractors, EPD developers
Vlaming (2018)	Analysis of the role of partnering in the circular economy transition of the infrastructure sector	Interviews, transition theory, and case study	Local and regional governments, national environmental and infrastructure agencies, industry associations, consultancies
Cao et al. (2019b)	Optimal recycling scheduling based on maximum performance and minimum cost	Analytic hierarchy process	Road agencies, road contractors
Mantalovas et al. (2020)	How NRAs communicate their CE practices	Survey with questionnaire	Road agencies, policy makers
Rangelov et al. (2021)	Investigations on the prerequisites, barriers, and path forward to the use of EPDs	Literature review and thematic analysis	Road agencies, policy makers, EPD developers, material manufacturers, consultancies
Rangelov et al. (2022)	Development and implementation of EPD for asphalt mixtures with waste plastics	Case study	Material manufacturers, road contractors, EPD developers, consultancies, policy makers
Zande (2022)	Identification of data requirements for a porous asphalt material passport	Survey with questionnaires and thematic analysis	Material manufacturers, road contractors, EPD developers, consultancies, policy makers

like terrestrial ecotoxicity and land occupation, are seldom included, highlighting a gap between initiatives and practice in current life cycle literature.

5.3. Preliminary attempts in decision-making system upgrade

Future smart pavement transformation with circular economy and digital tools goes beyond the life cycle framework that has been constructed. At this stage, it is still too early to draw any valid conclusions about the trend with limited studies (8 heterogeneous studies from theme 3). The research focus of these 8 articles, reports, and theses is listed in Table 5, in which the applied methods/tools and concerned stakeholders are also compared.

Generally speaking, the studies within theme 3 encompass a broad spectrum of perspectives on circular economy practices, extending beyond engineering solutions (Mallick et al., 2014; Cao et al., 2019b; Subedi et al., 2018) to include partnering and management (Vlaming, 2018; Rangelov et al., 2021; Mantalovas and Di Mino, 2019; Rangelov et al., 2022; Zande, 2022), as more and more pavement engineers have come to realize the transition will not occur with one-sided efforts. Among the included engineering solutions, both Cao et al. (2019b) and Subedi et al. (2018) tried to develop a decision-making system based on functions of pavement sustainability performances (technical-, cost- and environmental) while Mallick et al. (2014) have drawn attention towards the practical issues related to aggregates stocks. As addressed in several life cycle projects in Section 5.2, the transportation stage of materials shares a considerable proportion of the total life cycle impacts and costs. With regards to the sensitivity of pavement recycling impacts over the hauling effects, Mallick et al. (2014) rose their concerns on the increasing hauling distances due to the depletion of aggregates. Taking the greater Toronto area as an example, all aggregates had gone depleted within 50 km and the hauling distance to the nearest resources was expected to increase by 0.5 km annually (Aggregate Resources Task Force, 1998). Unfortunately, similar circumstances can be perceived in many other countries (Mallick et al., 2014). At the same time, it is documented in a previous study that by increasing the hauling distance from 20 km to 100 km, the impacts of pavement reconstruction with virgin aggregates would be 40% to 60% more than that of in-place recycling (Turk et al., 2016). Thus, Mallick et al. (2014) argued the risks behind the depletion of local aggregates should be taken into consideration to guarantee uninterrupted supplies of aggregates in a sustainable manner. This work offers a reference for dynamic systemic planning, which is pertinent to the development of pavement material passports capable of adapting to evolving system dynamics.

In comparison to the studies in the other two themes, another noticeable discrepancy is the engagement of road agencies and policy-makers through different approaches. There are 3 studies that are based on interviews and surveys with research interests of variety (Vlaming, 2018; Mantalovas and Di Mino, 2019; Zande, 2022). These applied social science investigation tools have enabled the communication of points of view from diverse stances. Mantalovas et al. (2020)'s survey with several European national road authorities helped academia and the pavement industry to understand the concerns on the road agencies' part, which would probably encourage better communication in the future. Besides the road authorities, Vlaming (2018) and Zande (2022) have even managed to involve more partners from regional and national governments, the industry sector, consultancies, and EPD

Table 6
Summary of the mentioned drivers of- and barriers to the circular economy transition in the pavement sector.

Factors	Drivers	Barriers
Technical	• Extensive lab experiments • Developing tools and technologies	• Limited field experiments • Unstandardized performance tests • Lack of understanding of some of the involved mechanisms during mixing • Inconsistent properties of secondary materials with different use histories
Market/Economic	• Reduced production costs • Developing LCCA evaluation	• Uncertainties behind the recyclability of mixtures containing other secondary materials • Sunk cost in the existing machinery • Dominating considerations of agency costs
Regulatory	• Stricter environmental policies for treating waste material • Successful practices in other countries	• Demand for policy support on standardization • Missing incentives for novel practices • Ambiguity on the ownership of data
Social/Environmental	• Decreased environmental impacts • Reduced construction level	• Inconsistent impact categories • Data inaccuracy • Negative environmental performance • Lack of education regarding the circular economy on the road user's side

developers. Their analysis of the survey and interview results has independently proved the role of partnering in the transition to a circular economy. Furthermore, efforts have not only been done on the academia's side. Rangelov et al. (2021), who are from the U.S. Federal Highway Administration, initiated an investigation on the prerequisites, barriers, and path forward to the use of EPDs, and later in (2022), they exemplified the implementation of EPDs for asphalt mixtures containing waste plastics. In their understanding, the promotion of current EPDs needs to be done through a few improvements: (1) the inclusion of EPDs should be required as a part of bidding; (2) a communication function among stakeholders regarding dynamic data changes has to be included; (3) standardization of background datasets and calculation methods is demanded to obtain accurate sustainability assessment.

5.4. Drivers and barriers

The previous section reviewed literature on circular economy practices in the pavement sector, focusing on three main themes. This section summarizes the drivers and barriers to systemic transformation. Various systems categorize these factors, with Kirchherr et al. (2018) proposing cultural, market, regulatory, and technology categories, and De Jesus and Mendonça (2018) suggesting soft (institutional and social) and hard (technical and economic) categories. In this review, factors are adjusted to technical, market/economic, regulatory, and social/environmental categories. Table 6 presents these factors in pairs based on the above-mentioned categories.

5.4.1. Technical factors

Moving toward the circular economy is a long-term event that is established on top of every single new product, process, and business mode. The technical knowledge of these elements constructs the foundation for future implementation. There is no doubt that extensive lab experiments have been conducted by global researchers. All of the 30 studies in theme 1 have included laboratory tests to analyze the performance of pavement materials that have applied new mixing techniques, different percentages of RAP, and waste materials. On the contrary, field tests have only been introduced in 11 studies, potentially owing to budget restrictions and non-favoring regulations. Whereas, the paradox is that if the pavement sector sticks with the current linear business mode, regulations have to be pushed by reliable field test results that could never be achieved of magnitude without regulatory support. Meanwhile, it is a challenging task to compare the existing results of each study as there are no unified guidelines for the inclusion and exclusion criteria for performance tests. The inconsistencies can not only be recognized in the types of performance tests but also the examined properties of the secondary materials with different origins and use histories. Table 7 refers to some of the studies that have mentioned this issue and the variety of the investigated material types indicates the universal concerns about the uncertainties behind an unknown history of the applied materials. Simultaneously, the limited knowledge of materials' existing behaviors makes it an additional challenge to predict the future performance of the pavement, especially considering the fast-changing traffic conditions and the climatic conditions that are less and less predictable due to global warming. This is certainly a significant constraint for more popular real-life employment of recycled materials, which also implies an important technical problem that should be addressed in the future development of material passports.

5.4.2. Market/economic factors

In De Jesus et al. (2018)'s words, besides re-engineering the existing process with technical solutions, another important fact about the circular economy is its capability of rewiring the system of supply and demand. In the transition to a circular economy, the market's response to changes in supply and demand is crucial. The high costs of asphalt production due to resource depletion pose challenges, with existing technology's sunk costs and uncertainties hindering innovation-driven transitions.

The emergence of LCCA, to a certain degree, could be regarded as an avenue to break the linear lock-ins and strong path dependencies. Based on a long-term view, it is reasonable to believe that the evidence-based LCCA gives a great opportunity for asphalt enterprises and road authorities to rethink the traditional practices that have been established on outdated supply and demand networks. However,

Table 7
Quotations regarding the influence of materials source and use histories.

Author (year)	Investigated material	Quotations
Praticò et al. (2013)	RAP	*"…Because RAP is removed from an old pavement, its composition will be affected by the previous maintenance and preservation activities that were applied to the existing pavement…"*
Zanetti et al. (2014)	CR	*"…Based on the Authors' experience, it can be concluded that CRs deriving from different sources and processes yield effects on field performance and emissions of bituminous binders and mixtures which may change considerably depending upon their physical and chemical properties…"*
Taherkhani and Noorian (2021)	Waste oil	*"…It is worth to mention that, the results drawn from this study cannot be generalised for all waste oils, as their source, chemical composition, impurities, type and temperature of use may be different…"*
Yousefi et al. (2021)	RAP	*"…The type and origin of RAs significantly affected the fracture toughness and fracture energy of the mixtures under all modes of loading at both…"*
Liu et al. (2022b)	Phosphogypsum (mixed with soil and crushed stone)	*"…Since the soil or crushed stone in different regions has different properties, the mix proportion of the PG has to be designed and optimized for each specific type of local resources, which involves extensive laboratory testing efforts…"*

when a closer look is taken at the range of investigated pavement life cycle stages in theme 2 studies, only 4 studies have covered the use stage while all the studies have given extra attention to the raw material extraction stage and production stage. Apparently, such an inclined emphasis is targeted toward the road agencies as the majority of the discussed economic advantages of using alternative materials are over the material phases. On the contrary, the work zone traffic management and use phases have more influence from the road users' perspectives even though these effects are often excluded from the system boundary of life cycle studies. The exclusion of road users could also be observed even in the theme 1 studies. The performance evaluation of proposed competing materials based on laboratory work and field tests is the core of the research work in this category. While a wide variety of physical, mechanical, and chemical tests have been applied in the existing literature, the field performance of the novel materials regarding their user-related indexes (such as macro texture, micro texture, roughness, and acoustic properties) is seldom included. Consequently, there is a lack of fundamental user-based performance information for current life cycle studies to stand on, reinforcing the omitted role of end consumers in the prevailing linear economic system and making it a daunting issue to predict the future behaviors of pavement systems (Liu et al., 2022a). As one of the elements supporting trustworthy assessment results from LCCA/LCA studies, the prediction of future performance that is mischaracterizing will possibly result in underperformance in budget allocation and mislead decision-making in road infrastructure management considering the potential cost of the adaption of pavement infrastructure to climate change. A quantitative study by Chinowsky et al. (2013) foresaw an increase of $2.8 billion in the costs of climate adaption for the American road system in 2050, compared to its expenses in 2010. Unfortunately, this crucial role of the fundamental prediction model included in the existing LCCA/LCA studies has barely been mentioned. The assumption that the ambient environment of pavement systems remains stable in the existing literature fails to capture the reality, thereby leading to an inclination for path dependencies.

The ascendancy given to agency costs and the neglect of user costs have further resulted in mismatching evaluation targets, setting obstacles for the ongoing transition. By comparing the studied secondary materials in Table 2 from theme 1 and Table 3 from theme 2, an evident discrepancy in the type of the investigated materials can be perceived. A possible explanation is the dominant considerations of agency costs, which are led by the dominance of road authorities in the linear top-down decision-making process. Thus, Despite LCCA providing an analytical basis, the information gap and user omission limit its effectiveness in driving change.

5.4.3. Regulatory factors

Even though most collected studies in the review are engineering-based and tend to focus on technical solutions for circular economy practices. The important role of institutional and regulatory factors has still been accentuated extensively in several research works regarding policy support, incentives, supervision, and cooperation. Within a linear framework, the characteristics of pavement infrastructure make the recommendations and requirements of the government almost the only decisive factor. Thus, in a dialogue for promoting circular transition in the pavement sector, the legislation framework can either stimulate sustainability transition or hinder circular economy initiatives, acting as a double-edged sword.

China's waste import ban serves as an example of policy driving circular initiatives. Challenges in landfilling prompted the reuse of waste materials in pavement systems. Stricter environmental policies changed societal perceptions of "waste," leading to innovative waste management suggestions. In a review article focusing on reusing waste plastic in asphalt production, Heydari et al. (2021) explicitly mentioned the urgency of treating plastic waste after China banned the import of recyclable wastes from developed countries. In this case, the stricter environmental management policies have forced the market to reflect on the fact that society might have often categorized materials as waste too quickly (Zhang et al., 2010). As a further response, other researchers such as Anwar et al. (2021) have suggested *"…a successful collection of waste systems ought to be set in place by waste management agencies in order to facilitate the separate collection of waste plastic…"*.

However, hurdles such as underdeveloped legal systems and unclear guidelines inhibit circular economy adoption, as evidenced by the limited utilization of RAP due to undefined policies. Another noteworthy example is undefined policies for stockpiling, which has entangled the utilization of RAP and other waste materials in real life, especially given the expanding array of potential alternatives and their impact on asphalt mixture homogeneity. For instance, in the Swedish road project Tvärförbindelse Södertörn (Karlberg, 2021), the road contractors and other industrial partners failed to manage the re-use of the excavated materials from a tunnel in a road project because the materials were too soon to be classified as waste following the current policy. The difficulties with stockpiling and the short time for qualification have discouraged companies from investing in recycled materials. Unfortunately, these challenges in return exacerbate the confidence of road authorities in permitting novel waste materials. Table 8 displays a few instances where researchers from all over the world urge for changes in the current legal systems. It is obvious that the lack of policy support can be found in the very early design and production stages of pavements, restricting the whole systemic change in the pavement sector.

Table 8
Quotations regarding the demand for policy support and standardized guidelines.

Author (year)	Location	Quotations
Presti et al. (2016)	the U.K.	*"...technological change of the asphalt plants is needed and it's sporadically happening, but also material characterisation and binder and mixtures design should be adapted to consider RA as the main ingredient..."*
Rudnicki and Jurczak (2020)	Poland	*"...In the authors' opinion, the above-described reclaimed material can, following appropriate processing, be used to substitute some of the new aggregate in concrete mixes for paving applications, even for the lower layers of pavement. Unfortunately, the Polish guidelines and specification do not provide for the use of aggregate reclaimed from concrete pavements for production of new PCC pavement mixes..."*
Wang et al. (2020)	China	*"...The waste tire recycling industry in China lacks policy support. The high cost of recycling and the environmental protection restrictions applied in the production process have reduced the interest shown by CR recycling companies..."*
Anwar et al. (2021)	Pakistan	*"...There is a need for cooperation among all investors and policymakers at all levels of government in order to allocate resources, as well as legislation, supervision, and compliance, for research and innovation to promote sustainable road infrastructure in developing nations..."*
Carmo et al. (2022)	Brazil	*"...The application of CDW in concrete has been successfully investigated and applied worldwide. However, local legislation frequently imposes rigid restrictions..."*

Theme 3 studies suggest a future transition involving government-stakeholder communication, transparent data, and standardized processes. The concerns on data accuracy and transparency have been extensively discussed in the life cycle studies for a long time, whereas, the developing coupling between LCA and EPD (Rangelov et al., 2021, 2022) requires additional standardization and constructing preliminary material passports for pavement (Zande, 2022) is bringing uncertainties of data ownership into the limelight. The promotion of the circular mode, to some extent, is established upon the decentralization of the current management system and engaging the stakeholders with responsibilities. Accordingly, it becomes crucial that the government sets up a welcoming environment for innovation and entrepreneurship with policy support and financial incentives, as well as a system where stakeholders can confidently take responsibility and initiative (De Jesus and Mendonça, 2018).

5.4.4. Social/environmental factors

While it is straightforward to consider the cost benefits of the circular economy for road agencies and users, defining its positive impacts on the environment and society requires more effort. The definition from Pearce and Turner (1990) sets up a great theoretical basis for understanding the role of the environment within the context of the circular economy. In their description, the values of the environment can be categorized into four functions: (1) amenity values; (2) a resource base for the economy; (3) a sink for residual flows; and (4) a life-support system.

These socio-economic values indirectly influence decision-making according to the values-beliefs-norms theory (Stern et al., 1999). The theory explains how values influence people's worldview about the environment affecting their perceptions of change and actions to reduce threats (Dietz et al., 2005). It is not an exaggeration to claim the vital role of values in decision-making, especially those with trade-offs among our preferences engaged. On the other side, it has also been addressed by Dietz et al. (2005) that when a decision becomes a routine, individuals or groups are more likely to choose it without referring to their values, which is a great example of the lock-in inertia in the linear economic model. However, the almost disdained road users on the demand side and their minimal engagement in the reviewed literature have adequately indicated the path dependency that the pavement sector is falling into. As a consequence, how to provoke road users' awareness of the circular economy and dare to take responsibility for making sustainable decisions, has an essential meaning for the transition.

The development of pavement LCA has provided a relatively comprehensive platform for assessing and presenting the environmental impacts of changes in a road system. Despite the drawbacks, pavement LCA has enabled a considerable amount of informed decision-making on the agencies' side. Unfortunately, there is a scarcity of studies that have applied LCA studies or other tools to educate consumers about circular business and "service as a product" (Mälkki and Alanne, 2017).

6. Conclusions and recommendations

In summary, this review provides a comprehensive overview of the historical development of the circular economy concept in the pavement sector. The conceptualization of the circular economy is still considered in its nascent stage, with noticeable efforts made by academia, the industry, and the authorities on various aspects. The analysis is supported by a systematic collection of 59 research papers and reports regarding three different recognized themes, including (1) historical practices of material recycling and reusing in the pavement system; (2) sustainability evaluation of traditional and novel pavement activities by applying life cycle studies; (3) systemic upgrade of pavement decision-making involving cooperation and digitization. Generally speaking, the evolving trend of circular economy practices can be characterized by expanding system boundaries and growing stakeholder engagement.

It is found that the transition heavily relies on the road agencies within the current road management framework, where cost considerations play a dominating factor. The drastically increasing costs of virgin materials have also become an essential drive for the explorations of possible alternatives. The global popular utilization of LCCA underscores the significant impact of financial factors. At the same time, the emphasis on the earlier life cycle stages in these LCCA works indicates the non-negligible inclination for agency costs. The overlooked transportation and end-of-life stages spotlight the losses of the opportunity to feature the impacts of climate change on the material selections.

Another two fundamental cornerstones of the circular concept implementation are the technical factors and the regulatory factors as the former enables the change with actual innovative technology and the latter allows and guides the change from a legislative perspective. The paradigm shift to the circular economy is inhibited by the missing legislation support and technical guidance, which has been addressed

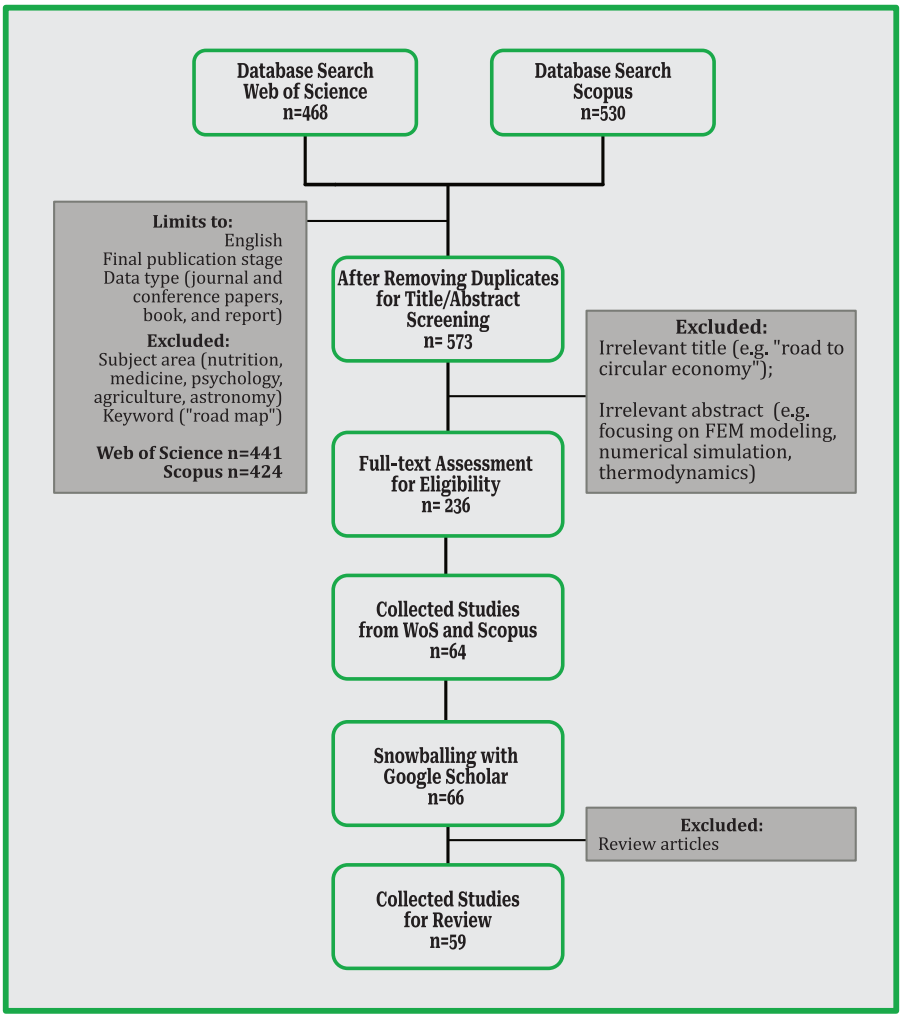


Fig. 5. Schematic of the publication collection process.

widely by global researchers and industrial partners. Especially when it comes to the future adoption of material passports and other digital tools for road management, it is of vital importance to have a decentralized system that is capable of engaging partners from other sectors, allowing the establishment of transparent and standardized databases and practice guidelines for future green procurement to stand on.

Simultaneously, there is a global consensus that climate change is a consequence of unsustainable social behaviors, a reality that extends to the pavement infrastructure domain. In practice, while the technological characteristics of pavement systems have been used to address the carbon lock-in, the influence of its social counterpart is often masked. In comparison to the legal systems which may change over decades, the evolution of social norms and cultural values is expected to take centuries to come into shape. As a consequence, the lack of understanding of how behavioral patterns in the pavement decision-making process can be altered poses barriers to truly recognizing the role of the environment in the context of the circular economy.

The complexity of the pavement system has brought unavoidable challenges to the systemic transition to the circular economy. Based on the analysis of drivers and barriers in the existing multi-dimensional practices, this review has identified the following potential research and management directions for the paradigm shift to the circular economy:

1. development of technical guidance and legal system that allow and encourage sustainable transformation;
2. establishment of transparent and standardized data along the whole supply chain of pavement materials
3. construction of unified data management systems with safe and traceable ownership;
4. build of a welcoming environment for innovation and entrepreneurship, as well as a system where stakeholders could confidently take responsibility and initiative.

CRediT authorship contribution statement

Zhuhuan Liu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Nicole Kringos:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix

See Fig. 5.

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