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Review

Glass waste circular economy - Advancing to high-value glass sheets recovery using industry 4.0 and 5.0 technologies

Seyed Ali Delbari, Lucas A. Hof*

Department of Mechanical Engineering, École de technologie supérieure, 1100, rue Notre-dame Ouest, Montreal, Québec, H3C 1K3, Canada

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ABSTRACT

Due to the ongoing development of urban infrastructure and higher living standards, waste glass has become a significant component of municipal solid waste that cannot be disregarded. To address this issue, researchers have been looking for sustainable solutions to establish Circular Economy best practices for the full value chain of products made of glass, particularly for waste from high-quality glass sheets. Unfortunately, most of this waste is either dumped in landfills or recycled in an open-loop manner, due to its diverse composition and low volume. However, with the advent of Industry 4.0 and 5.0 technologies, including machine-to-machine communication, artificial intelligence, Internet of Things, collaborative robots, dynamic life cycle assessment, and advanced remanufacturing techniques, it could now become possible to characterize and recover end-of-life high-quality glass sheets like chemically strengthened glasses, e.g. used in smartphone screens, real time in smart factories for use in other high-tech applications. Such smart factories can economically produce on-demand batch-size 1 products, marking a fundamental transition from conventional recycling methods to a sustainable solution. This paper delves into the integration of Industry 4.0 technologies in glass recycling research and the potential contributions of Industry 5.0, addressing its societal implications. It also introduces an intelligent method to assess and optimize the lifespan of smartphone screen glass, suggesting potential reuse or remanufacturing solutions.

1. Introduction

The use of glass dates back to around 3500 BCE, with evidence from ancient civilizations in northern Syria, Egypt, and Mesopotamia (J. David Musgraves & Juejun HuLaurent Calvez, 2019; Mohajerani et al., 2017). Glass is a fascinating material that has been created by humans and has universal appeal. It is a transparent and brittle substance with a multitude of uses in modern fields such as optics (Wei et al.,2019), optoelectronics (Granados et al., 2021), manufacturing (L. A. Hof and Wuthrich, 2021), architecture (Arbab and Finley, 2010), medicine (Hench et al., 2010), and arts (Bardin, 2019). This is mainly due to its remarkable characteristics, including low permeability, optical clarity, chemical inertness, and high inherent strength (Baino et al., 2021; Lu et al., 2017). Most of the necessary elements for making this non-crystalline (amorphous) material can be found in the earth's crust (Le Bourhis, 2007). In the glass manufacturing process, the raw materials' constituents, such as silica, soda and lime, come together to form a brand-new, random network linked by oxygen bridges. Glass can be manufactured using thousands of various chemical compositions, each of which has its own unique optical, chemical, electrical, mechanical, and thermal properties (Testa et al., 2017).

Fig. 1 presents the global glass manufacturing flow map for the year 2014, illustrating the trajectory, i.e., the full value chain, of glass from its raw material origins to its end-of-life cycle. The width of each pathway is directly proportional to its mass, and the corresponding values are expressed in millions of tons (Mt). This diagram highlights the initial use of 144 Mt of virgin raw materials and 28 Mt of cullet (crushed waste glass, ready for remelting, typically sourced from manufacturing rejects or breakage), leading to the production of 96 Mt of flat and 97 Mt of container glass products, and the generation of 22 Mt of process emissions, mostly anthropogenic carbon emissions, such as carbon dioxides (CO_2). Fig. 1 further details the reworking and fabrication processes, resulting in various glass products predominantly used in the building and beverage industries. The lifecycle is characterized by limited stock accumulation due to the short lifespan of container glass, which is typically recycled or landfilled, underscoring the industry's challenges in sustainable management and recycling (Westbroek et al., 2021).

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* Corresponding author.
E-mail addresses: seyed-ali.delbari.1@ens.etsmtl.ca (S.A. Delbari), lucas.hof@etsmtl.ca (L.A. Hof).

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The rising demand for glass products has resulted as well in a significant increase of glass waste (Qaidi et al., 2022). Landfilling glass waste is not environmentally sustainable, as it consumes valuable landfill space and involves transportation, which contributes to pollution. Recycling glass, in contrast, is essential for efficient waste management. It allows the recovery and reuse of materials, preserving natural resources and reducing the need to extract and process virgin materials (Salzmann et al., 2022). Furthermore, it should be noted that the availability of raw resources is critical for efficient management and industrial operations. Therefore, recycling waste helps to reduce the environmental harm caused by human industrial activities through lowering the demand for industrial raw materials (Benzerga et al., 2015). It cannot be overlooked that waste glass has now become a significant constituent of Municipal Solid Waste (MSW) that comprises various types including flat glass, scientific glass, container glass, bulb glass, decorative glass, among others, due to the ongoing progress of urban development and the increase in people's quality of life. For instance, in the USA, glass constituted 5.17% of the total MSW landfill in 2018 (U.S. Environmental Protection Agency (EPA), 2021). When glass is landfilled or incinerated, it does not decompose, but rather adds to the total amount of waste produced by these waste management methods. Also, it is not possible to use glass for energy recovery purposes (Cocking, 2003; Larsen et al., 2009a; Yao et al., 2021). Nevertheless, through waste glass recycling, primary material resources, energy, and water can be conserved (Šooš et al., 2021). Additionally, this approach helps to reduce waste accumulation in landfills, where every ton of glass waste can add approximately 1.5 m^3 to the landfill volume (Ferdous et al., 2021). Hence, this equates for the USA alone already to approximately 7.5 Mt of waste, necessitating 11.3 Mm^3 landfill volume for its management. Today, recycling is essential for humanity to have a sustainable future on this planet. Communities around the world are urged to participate in a glass recycling system that is environmentally friendly and sustainable (Franjić and Freestone, 2019).

Recognizing the impact of waste management, particularly in glass recycling, highlights the importance of integrating these practices into the wider context of sustainable development and the circular economy. Sustainable development is an adaptable and comprehensive approach that offers a framework for addressing complex problems by sharing responsibilities among socially responsible corporations and society (Blengini et al., 2012). The goal of sustainability is to minimize adverse effects of development while preserving a high living standard for future and current generations (Srour et al., 2012). The World Commission on Environment and Development identifies three dimensions of sustainability that should be jointly considered: social welfare, environmental protection, and economic viability (Mirdar Harijani et al., 2017). In this context, the concept of the circular economy is widely acknowledged as moving away from traditional end-of-life solutions, focusing instead on comprehensive and sustainable strategies. The idea originated in the 1970s as a competing paradigm that integrates conservation and lifespan concepts. In accordance with the waste hierarchy principle, circular economy always prioritizes the highest possible value of utility, material, component, and product (Keβler et al., 2021).

As such, scientists have been seeking sustainable solutions to enhance the efficiency of circular economy actions for the glass value chain in recent years (Huang et al., 2024; Ogundairo et al., 2019; X. Yuan et al., 2024). Among others, the demand for more efficient production of high-quality glass, such as Chemically Strengthened Glass (CGS) used as smartphone screen, has increased (Svenson et al., 2014). However, the production of such glass involves expensive post-processing (Berneschi et al., 2021), and simply recycling is wasteful. In addition to examining conventional recycling methods, the present literature review uniquely proposes the exploration of innovative possibilities for recovering high-quality glass products. For the first time, it delves into the application of advanced Industry 4.0 and 5.0 technologies (Golovianko et al., 2023; X. Xu et al., 2021), establishing a new precedent in the field of glass recycling and circular economy. This approach aims to contribute to a progressive and efficient implementation of circular economy practices in the glass industry, particularly for valuable products such as high-quality CGS sheets.

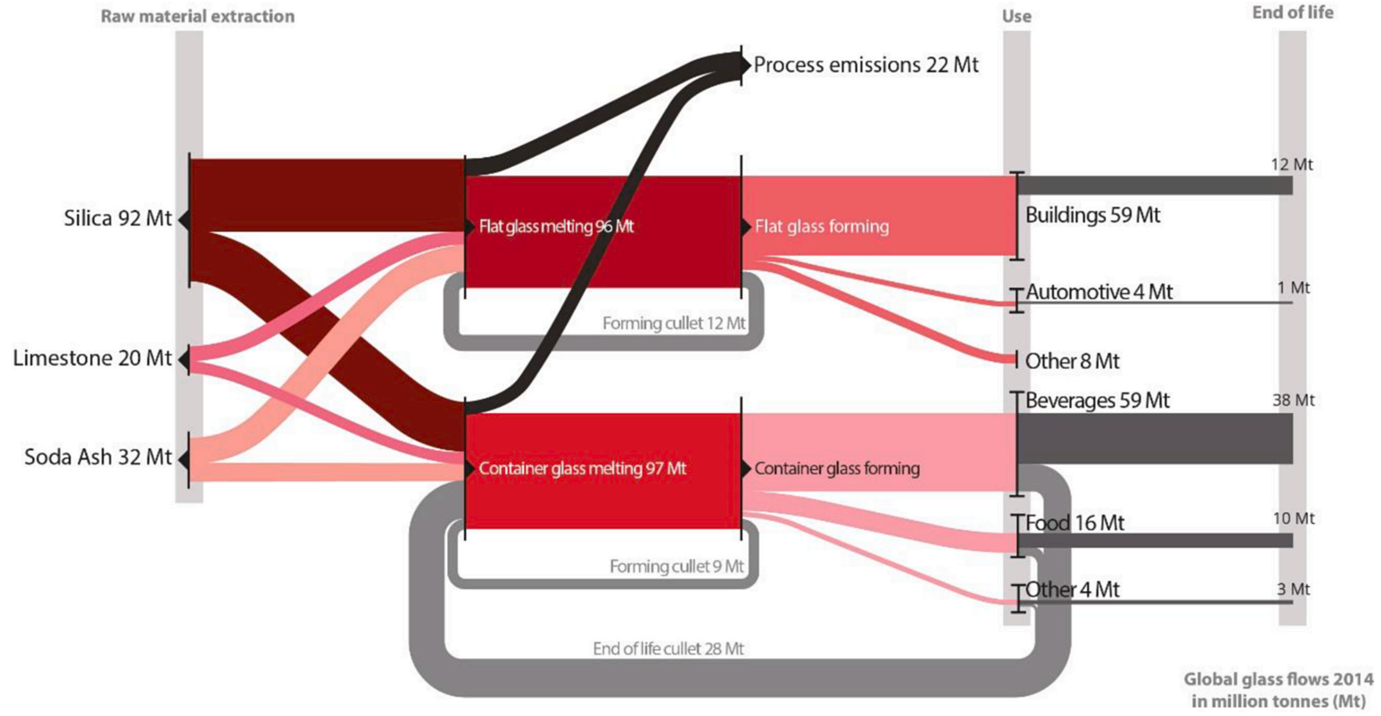

Fig. 1. The global glass flows in 2014, expressed in millions of tons (Mt), tracking the journey of glass from raw materials to end-of-life (adapted from (Westbroek et al., 2021)).

2. Research methodology

This review study uses a systematic literature review method to identify and analyze relevant academic papers through a structured approach, formulating a theoretical framework to categorize findings primarily aimed at evaluating existing glass waste management strategies and exploring sustainable solutions. The research methodology is detailed across several sections, starting with defining research questions (2.1), describing data sources and collection methods (2.2), detailing keywords for the literature search (2.3), and outlining paper selection criteria (2.4), culminating in the introduction of the theoretical framework (2.5) that guides the entire review of glass recycling and waste management literature.

2.1. Research questions

This section outlines the key research questions addressing the strategies, challenges, environmental impacts, and technological innovations in glass recycling and waste management. These questions guide the study's focus and help identify future research directions in the field. These questions are defined as follows.

1. What are the current strategies and challenges in glass waste management?
2. What are the environmental implications of glass waste?
3. Are current conventional recycling strategies suitable for high-quality glass sheets like CSGs?
4. How can Industry 4.0 and 5.0 technologies contribute to solving the current challenges in glass recycling and waste management?
5. What future research directions can be suggested in the domain of glass waste management for CSGs?

2.2. Data sources and collection process

The systematic literature review relied on research papers available from Google Scholar, Science Direct, Scopus, and Web of Science, databases widely recognized in the field of industrial engineering. The collection process was continuous and not restricted by any time frame to ensure a comprehensive review.

2.3. Keywords definition

An initial search was carried out to define the scope-specific keywords. These included: glass recovery management; glass recycling challenges; glass open-loop recycling; glass closed-loop recycling; glass surface defects detection; glass degradation; Artificial Intelligence (AI) applications in the glass industry; Machine-to-Machine (M2M) communication; glass remanufacturing; sustainability; intelligent materials. Additional keywords for open-loop recycling included construction materials, foam glass, glass ceramics, and filters for water/wastewater treatment.

2.4. Eligibility criteria

The eligibility criteria were established to effectively screen the articles. To be considered in the present review study, papers had to be peer-reviewed, published in English, and dated within the last 15 years. Book chapters, reference papers, and conference papers were also included if necessary. Articles were further screened by initially reading the title and abstract, followed by a full reading of the document. Papers that focused on unrelated topics were excluded after the first screening step (title and abstract reading).

2.5. Theoretical framework

The theoretical framework explores the incorporation of Industry 4.0 and 5.0 technologies into glass waste recycling, emphasizing technological integration, environmental sustainability, economic viability, social implications, and policy adaptations. It aims to guide research into the impacts of these technologies on recycling, identify research gaps, and propose future directions. Contributions are analyzed according to identified research themes, focusing on current glass waste management strategies and technologies that support a circular economy. Additionally, the framework proposes a system to evaluate the degradation state of end-of-life high-quality glass sheets to aid in recovery potential assessment and decision-making. Fig. 2 illustrates the structure of this review paper in detail.

3. Issues, challenges, and problem formulation

Before delving into sustainable solutions for end-of-life CSGs, this review study starts by examining the current state of glass recycling practices. While these methods are effective for specific types of glass, they cannot be universally applied to all glass varieties. Particularly, when considering CSGs and, more specifically, smartphone screens, several challenges emerge.

- Smartphone screens are not engineered for easy disassembly post-use. Hence, either effective disassembly solutions must be developed, or smartphone manufacturers should pivot towards a more sustainable assembly process;
- To gauge the degradation of CSGs, it is crucial to determine the required material characterizations and develop non-destructive assessment methods;
- Smartphone screens are susceptible to surface damage, including scratches and fractures, such defects can adversely affect their functionality;
- Currently, there is a lack of a standardized method or technique to evaluate the degradation state of CSGs, crucial for deciding the appropriate level of recovery;
- Given the tension profile across CSGs' thickness, their remanufacturing is more complex than it might seem initially.

Indeed, these challenges are difficult and complex to address. Nevertheless, emerging technologies present hope. While this review will not address every possible related issue, it aims to provide a perspective, encouraging researchers and the glass industry to lead the paradigm shift towards more sustainable solutions. Beyond traditional glass recycling methods, this study explores potential solutions for smartphone screens characterization, surface crack detection, and remanufacturing techniques. Additionally, this paper highlights prospective avenues for researchers in the high-quality glass circular economy.

4. Results and discussion

4.1. Environmental necessity of glass circular economy

Since glass waste has a relatively high weight and is dense compared to other types of waste, it causes significant problems for the environment. In order to prevent environmental issues that could arise from transferring glass waste to a landfill, it is crucial that glass waste be reused or recycled (Bisikirske et al., 2019). Waste glass is very stable and does not degrade naturally, wasting finite land resources like silica. Additionally, waste glass might include dangerous elements like the lead found in Cathode Ray Tubes (CRTs), which will contaminate the water and soil and harm the environment's ecology (Larsen et al., 2009b; Qin et al., 2022; Xie et al., 2012). Theoretically, glass is completely recoverable and may be recycled indefinitely without losing its qualities or functionality, providing advantages for the environment, the economy, and society. For example, recycling 3000 standard-sized glass bottles can prevent the generation of 1000 kg of waste (Aguilar-Jurado et al.,

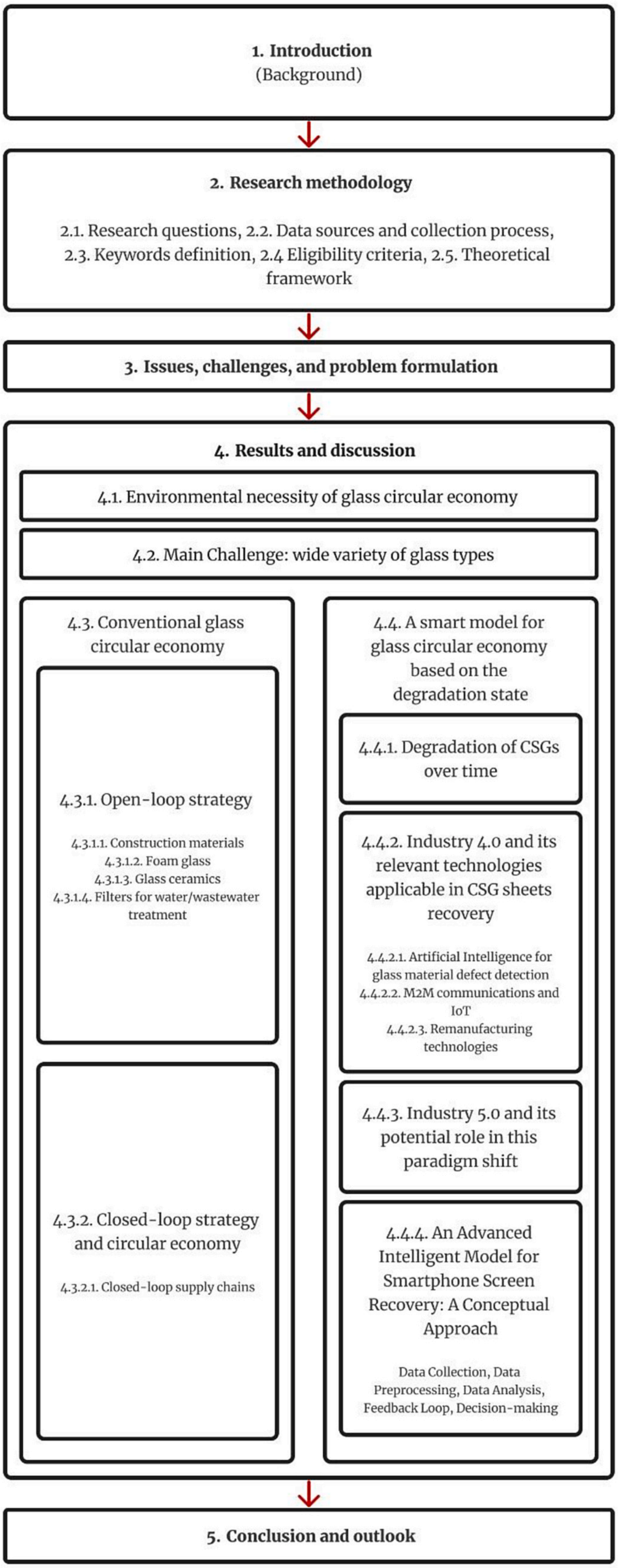

Fig. 2. The structure of the review paper.

2019). Indeed, recycling glass has positive health effects, too, and lower healthcare expenses since it diminishes water and air pollution (Meyers, 2012). It is interesting to note that by using conventional waste glass recycling techniques, such as melting the waste glass to manufacture new glass containers, 315 kg of CO$_2$ might be saved for every ton of waste glass melted (Ling et al., 2013). Based on a survey in 2014, the glass industry is responsible for approximately 86 Mt of CO$_2$ emissions, accounting for roughly 0.3% of global emissions (Westbroek et al., 2021). More specifically, for every 10% increase in cullet used in container glass recycling, the required melting energy is decreased by 2.5%, and emissions of SO$_x$ by 10%, NO$_x$ by 4% and particulate matter by 8% (*Kirk-Othmer Encyclopedia of Chemical Technology, 2000*). Recycling glass, when reuse and recovery are not viable, not only conserves natural resources needed for its production, like sand, sodium carbonate, and limestone, but also promotes the circular economy. This approach significantly reduces land pollution, leading to financial savings and decreased soil degradation due to resource extraction (Aguilar-Jurado et al., 2019). Indeed, one ton of cullet substitutes 80 kg of dolomite, 150 kg of limestone, 190 kg of soda ash, 50 kg of feldspar, and 700 kg of sand in the production of container glass (Moser, 2012). It is also important to mention that sand, the main source of SiO$_2$, is a finite resource, contrary to popular belief. Sand is the only other resource that receives more extraction than water. Sand and gravel made up between 68% and 85% of the 47 to 59 billion tons of materials that are annually explored around the world. A large amount of the dredged-up sand (more than 75%) is used in the construction industry as a key ingredient for concrete and glass, triggering substantial harm to coasts and ecosystems. Even though there is little awareness that resources are restricted worldwide, sand extraction is increasing globally (Hayes and Petrović, 2020; Ogundairo et al., 2019).

After glass reuse, recycling is favored, stemming from emissions reductions in the melting furnace and across the entire lifecycle. However, despite these benefits, global recycling rates for all types of glass, including container glass, flat glass, etc., remain at a low level. Current estimates place recycling volumes at 27 Mt annually, constituting a mere 21% of the total glass production (Westbroek et al., 2021). When considering container glass, the worldwide recycling rate hovers around 32%, although certain countries have achieved rates as high as 70%. The incorporation of recycled content into flat glass manufacture is restricted to as low as 11%, a limitation attributed to the necessity of maintaining precise chemical composition in soda-lime-silica glass, which is among the most used glass types (Kilinc and Hand, 2015). In contrast, container glass possesses the potential for reuse, yet the actual reuse rate stands at a meager 4% within the European Union (EU) and even lower elsewhere globally (Westbroek et al., 2021). This prompts a crucial examination of the underlying reasons for the persistently low rates of reusing and recycling various types of glass across the majority of the world.

4.2. Main challenge: wide variety of glass types

While container glass is widely recycled around the world, the majority of other types of commercial glass waste are either downcycled or directly sent to landfills. This is largely due to the fact that there is not sufficient infrastructure in place to properly collect, separate, and purify glass that differs in composition and surface treatment from container glass (Bristogianni and Oikonomopoulou, 2022). In fact, container glass has the ability to be recycled an unlimited number of times. However, recycled glass is typically made up of a mixture of various colored glass particles and usually contains a wide range of debris, such as metals, soil, plastic, paper, and food waste. The presence of various types of debris and different colors of glass are the main challenges that make it difficult to reuse recycled glass in the production of new bottles (Disfani et al., 2011; Vellini and Savioli, 2009). Therefore, the proper sorting of container glass waste is crucial. In certain cities, citizens are responsible for separating glass waste based on color, with different containers provided for amber (brown), green, and white (clear) glass bottles (J. David Musgraves & Juejun HuLaurent Calvez, 2019). However, this method presents challenges such as requiring public awareness and participation, and the need for a well-organized collection infrastructure to manage separate bins effectively. Additionally, even with color sorting, further inspection is required before recycling to remove contaminants and ensure the quality of the recycled glass.

Flat glass, holding a roughly equal share in the glass industry alongside container glass (Westbroek et al., 2021), defined as a type of glass used in daily applications such as (car) windows, touch screens, and display screens, has diverse compositions depending on its purpose, making it challenging to sort for recycling. The flat glass recycling heavily relies on how end-of-life vehicles and construction and demolition wastes (C&DW) are handled. Indeed, around 70% of the worldwide production of flat glass is utilized in the construction and building industries, 10% in the manufacture of motor vehicles, and only the remaining 20% for other purposes. Effective management of end-of-life vehicles and C&DW waste streams is crucial for the recycling of such glass (Butler and Hooper, 2019). Table 1 displays the primary characteristics of the three most widely used types of flat glass, namely soda-lime-silica glass, aluminosilicate glass, and borosilicate glass. For instance, in the case of C&DW waste, it is important to ensure that flat glass is separated from other construction materials during the recycling process, as glass shares similar physical properties with many other inorganic, nonmetallic materials found in such waste, making separation difficult. As a result, despite its recyclability, end-of-life building glass is not typically recycled to create brand-new glass items because of the absence of a flat glass collection system and the complicated separation process (J. David Musgraves & Juejun HuLaurent Calvez, 2019).

Table 1

Mechanical and physical features of various glass types used in construction (reported values are valid over a temperature range of 20–300 °C) (Bristogianni and Oikonomopoulou, 2022; J. David Musgraves & Juejun HuLaurent Calvez, 2019).

Property	Soda-lime-silica glass	Aluminosilicate glass	Borosilicate glass
Composition	73% SiO_2, 17% Na_2O, 5% CaO, 4% MgO, 1% Al_2O_3	57% SiO_2, 20.5% Al_2O_3, 12% MgO, 5.5% CaO, 1% Na_2O	80% SiO_2, 13% B_2O_3, 4% Na_2O, 2.3% Al_2O_3, 0.1% K_2O
Density, ρ (kg/m^3)	2500	2480	2200–2300
Poisson's ratio, ν	0.23	0.22	0.20
Young's modulus, E (N/mm^2)	73000	74000	63000
Knoop's hardness	6	5.3	4.5–6
Refractive index, n	1.52	1.51	1.47
Soft point (°C)	730	915	780
Anneal point	548	715	525
Specific heat capacity, CP (J/(kgK))	800	840	830
Thermal conductivity, κ (W/(mK))	1.05	0.96	1.2
Coefficient of thermal expansion, CTE (10^{-6}/°C)	8.5	4.2	3.4
Applications	Building sector, container glass, window panes, Mirrors, Automotive industry	high temperature thermometers, combustion tubes, Mobile phone screens, fiber glass	Optical glass, packaging, lightbulbs, household ovenware, pharmaceutical, laboratory glassware

4.3. *Conventional glass circular economy*

MSW is a more complex type of solid waste compared to waste generated by industrial or agricultural activities as it is produced in urban areas where small increases in income can lead to changes in people's consumption habits. These changes result in a broader variety of waste and larger quantities of it, hence creating a greater challenge for municipalities to manage. In contrast, industrial or agricultural activities tend to produce more consistent waste streams (Troschinetz and Mihelcic, 2009). Glass materials are a significant component of MSW, and there have been many studies conducted on their recycling. Basically, there are two types of glass recycling: open-loop and closed-loop strategies. Poor-quality glass waste that cannot be used in the manufacturing of glass products is typically recycled through open-loop recycling. In contrast, closed-loop recycling involves processing waste glass to remove impurities and converting it into new glass products. This reduces the energy and raw material costs associated with glass production. In other words, in comparison with the glass manufacture using new raw materials, closed-loop recycling offers the benefits of conserving energy and materials, and reducing pollution. However, using high-quality recycled glass is essential for such glass remanufacturing approaches (Qi et al., 2019; Yao et al., 2021). Fig. 3 schematically presents an overview of the different recycling strategies used in the glass industry, which contrasts the open-loop and closed-loop methods commonly employed in conventional glass recycling. The following article sections (4.3.1 and 4.3.2) elaborate in detail on each of these strategies, providing a thorough exploration of their specific methodologies and applications in the context of glass recycling.

4.3.1. *Open-loop strategy*

There are several instances of successful open-loop methods where waste glass is effectively recycled and utilized as fractionators for firing ammunition and lighting matches (Ismail and AL-Hashmi, 2009), as a filtration medium to remove suspended particles from water (Soyer et al., 2010), e.g., for waste-water treatment, as an ingredient to produce ceramics, fiber glass, and various composite materials (Gorokhovsky et al., 2005; Zabihi et al., 2020), as raw materials for the production of glass beads or pellets utilized in reflective roadway paint, as an alternative aggregate in parking lots, pavement, and asphalt concrete (Emersleben and Meyer, 2012; Lu et al., 2019), and as a raw material to manufacture abrasives used in sand-blasting (Dyer, 2014; Ismail and AL-Hashmi, 2009; Mohajerani et al., 2017). Some of these solutions are discussed in more detail in the sections below.

4.3.1.1. Construction materials. Scientists are looking at using recycled glass instead of natural resources like cement, due to the high disposing costs of discarded glass and strict environmental requirements (Guo et al., 2020). Crushed waste glass can be used as a replacement for coarse and/or fine aggregates, as recycled glass cullet and recycled fine aggregates, in concrete due to its probable pozzolanic activity and chemical composition (Mohajerani et al., 2017). This approach offers several benefits. Firstly, there is less energy embodied in the production, because glass melting is avoided as this is not needed for its incorporation in concrete mixtures. Secondly, the process of dealing with waste glass would be simplified, as there is no need for separation based on the color and composition of the glass waste. Third, since concrete is commonly employed in infrastructures, a sizeable amount of glass can be used. Finally, the concrete matrix allows for the immobilization and containment of hazardous glass components. Existing reviews indicate that utilizing waste glass in concrete holds great promise (Hamada et al., 2022; Harrison et al., 2020). Nevertheless, there are conflicting perspectives on how glass aggregates, when employed as a replacement, affect the strength and durability of concrete and mortar. The technical advantage of glass aggregates over limestone aggregates is their low thermal conductivity, which leads to better thermal insulation values of

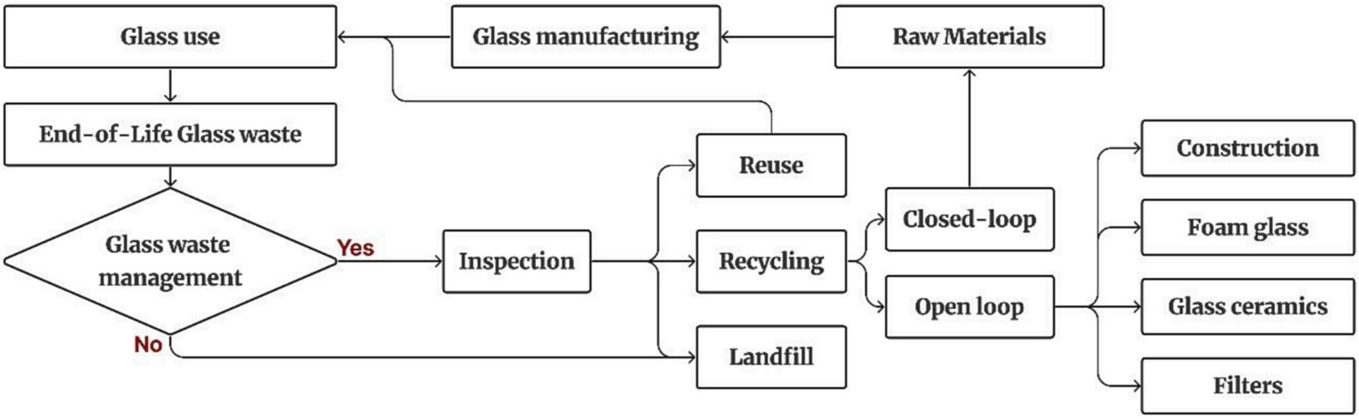

Fig. 3. The open-loop and closed-loop strategies in conventional glass recycling practices.

concrete. Furthermore, adding crushed waste glass to concrete also makes it more resistant to mechanical wear. Nonetheless, alkali-silica interactions, which can occur when waste glass is used as aggregates, produce expansive compounds that can diminish the mechanical qualities of concrete (Abdelli et al., 2020a,b). Additionally, the water absorption rate of waste glass is around 14% lower than that of natural sand (Jani and Hogland, 2014). Overall, due to its favorable properties, crushed waste glass is a promising aggregate for making concrete and its effects on cement-based materials have been widely studied.

As the potential benefits and challenges of using crushed waste glass in concrete are increasingly recognized, detailed empirical studies have emerged to examine the specific effects and applications of this recycled material. In a study on concrete development that used crushed waste glass, Ismail and AL-Hashmi (2009) found that specimens with 20% waste glass content had compressive strengths that were 4.23% higher and flexural strengths that were 10.99% higher than the control specimen after 28 days. Yang et al. (2021) discovered that adding recycled glass cullet and recycled fine aggregates to mortars increased their high temperature resistance, but applying too much glass material mechanically softened the mortars and prevented them from withstanding high temperature loadings. To balance these conflicting effects, the use of recycled glass cullet and recycled fine aggregates should be carefully monitored. Lu et al. (2020) investigated the combined use of recycled glass cullet and recycled fine aggregates in cement mortars. They found that the joint utilization of recycled glass cullet and recycled fine aggregates was feasible from both durability and mechanical perspectives. The inferior strength brought on by recycled glass cullet alone could be reduced by the combined recycling of recycled fine aggregates and recycled glass cullet, and the significant drying shrinkage of cement mortars brought on by the addition of recycled fine aggregates alone could be compensated by the usage of recycled fine aggregates. Additionally, compared to mortar made entirely of recycled glass cullet, the combination of recycled glass cullet and recycled fine aggregates may reduce the number of larger pores and increase strength. Similarly, a recent experimental study by Surendran and Akhas (2024) highlighted the successful incorporation of toughened glass (tempered glass) waste as coarse aggregates in high-performance concrete, showing significant improvements in mechanical properties. The optimal replacement of traditional coarse aggregates with 50% toughened glass waste was found to enhance the flexural strength of the concrete significantly.

There are also multiple studies that focus on utilizing waste glass in asphalt pavements. Specifically, a study by Huang et al. (2007) looked into asphalt surface layers. They found that asphalt mixtures containing 10–15% crushed waste glass showed good performance. To ensure safety and prevent problems, such as tire punctures and skin cuts, the maximum size of recycled glass aggregate utilized is typically around 4.75 mm. To maintain stripping resistance, an anti-strip agent, such as hydrated lime is additionally applied. However, it has been noted that employing asphalt with larger size and a higher glass content might result in issues like inadequate bonding strength and friction. Asphalt containing recycled glass can be manufactured and paved using the same equipment and methods as conventional asphalt.

Despite existing research, it's essential to acknowledge the challenges and limitations of using waste glass in construction, as highlighted below.

- Alkali-silica reaction (ASR): Glass, primarily silica, can react with concrete's alkaline components, causing expansion and potential structural damage (Mehta and Ashish, 2020).
- Workability and water absorption: The angular shape of glass particles can decrease concrete's fluidity. Differences in water absorption rates between glass and traditional aggregates may affect concrete's consistency and durability (Abdelli et al., 2020b).
- Variability in glass composition: Waste glass composition varies by source, potentially affecting concrete performance when used as aggregate (Ahmad et al., 2022).
- Optimal sizing and dosage: Proper sizing and dosage of glass are vital. Large particles or excessive dosages can weaken concrete (Ahmad et al., 2022).
- Economic viability: The use of waste glass depends on local availability and recycling infrastructure. Processing costs might not always compete with traditional materials (Nodehi and Mohamad Taghvaee, 2022a).
- Environmental concerns: Although beneficial for waste reduction, the environmental impact of processing glass for concrete, including energy use and emissions, needs consideration (Ahmad et al., 2022).

Future research should address these issues to develop more sustainable solutions for waste glass recycling in the construction sector.

4.3.1.2. *Foam glass.*

Foam glass, also known as cellular glass (Vaisman et al., 2016), is commonly employed for insulation against heat and noise and to stabilize soil. Foam glass is made by creating gas inside of glass at temperatures between 700 °C and 900 °C. This allows the gas to expand and build a structure of cells inside the glass, resulting in a porous substance. Nowadays, foam glass manufacturers utilize as much as 98% of recycled waste glass in their products (Q. Xu et al., 2012). Benzerga et al. (2015) created glass foams by combining two types of recycled glass cullet (one from CRT and the other from soda-lime silicate glasses) with different foaming agents. The cullet was mixed with the foaming agent (either AlN, SiC, C, or a combination) after being pre-dried for 12 h at 150 °C. This mixture was then placed in a heat-resistant steel mold and heated to the desired temperature of 850 °C for 30 min. When carbide or nitride foaming agents were used (such as AlN or SiC), the resulting foams were low-loss, i.e.

demonstratingthe ability to transmit electromagnetic waves with minimal energy loss, and homogeneous, making them suitable for use in antenna devices. Carbon was also utilized as a foaming agent, and although only a small amount reacted, this resulted in foams that exhibited significantly improved electromagnetic absorption capabilities. This enhancement is attributed to a notable increase in dielectric loss, rendering these foams particularly effective for applications that demand efficient electromagnetic absorption. The researchers found that with recycled glass cullet as the raw material, the potential for creating carbon-filled glass foams at affordable prices is substantial. Siddika et al. (2023) utilized waste glass from automotive vehicle windows/windshields and fly ash, which were then activated using a sodium hydroxide activator. After using chemical foaming to increase porosity, the researchers applied low-speed mechanical foaming to stabilize the pores. Then, to create robust and durable glass foams, the resulting paste was sintered at 700–800 °C. Low shear stress was applied to the paste during low-speed mechanical foaming to prevent pore coalesce. To decrease the production of anisotropic pores, a low concentration of hydrogen peroxide was utilized, while water and hydrogen peroxide were reacting to produce oxygen (O_2) bubbles. The raw glass foam grew a uniformly distributed pore structure as a result, which was further stabilized after hardening. The findings of this study suggest that by combining chemical and mechanical foaming approaches, the precuring stages and prolonged activation in the gel casting technique can be avoided.

Despite the importance of this strategy in a viable glass circular economy, there are challenges to consider for future research.

- Pore structure control: Uniform pore structure is critical in foam glass for its insulative properties. Controlling mechanical and chemical foaming processes is essential to prevent defects like anisotropic pore formation, impacting performance (Siddika et al., 2023).
- Complex chemical reactions and material interactions: High-temperature chemical reactions are needed to decompose and integrate various waste materials, including glass. These reactions are crucial for forming foam glass and require controlled conditions like temperature and material ratios (H. Wang et al., 2023).
- Consistency and availability of waste: The variability in glass waste's chemical composition and physical properties can affect foam glass's consistency and quality (L. P. Wang et al., 2023).
- Crystallization issues: Post-consumer container glass is more prone to crystallization than other waste glass types, such as flat glass. Crystallization hampers foam expansion, increases open porosity, and affects thermal insulation (Smiljanić et al., 2023).
- Environmental impact: Recycling glass waste into foam glass reduces waste but the production's environmental impact, including energy use during high-temperature sintering, must be considered for sustainability (L. P. Wang et al., 2023).
- Economic feasibility: The economic viability of producing foam glass from waste involves factors like material costs, energy consumption, and production scalability (Fernandes et al., 2023).

Addressing these issues can promote the adoption of this strategy in industrial-scale glass waste management.

4.3.1.3. Glass ceramics. Ceramic materials, created through high-temperature manufacturing to produce non-metallic and inorganic solid products, possess specific properties that make them valuable in various engineering fields. Due to the extensive range of ceramic applications and the high-temperature production process, ceramic products are excellent candidates for using glass cullet as a substitute for natural resources. Nevertheless, the manufacturing process is energy-intensive and has significant environmental consequences (Silva et al., 2017). While incorporating glass cullet into ceramic products has its advantages, it is suggested that only glass that cannot be recycled through a closed-loop strategy should be considered for this purpose (Silva et al., 2017). When glasses with appropriate compositions are subjected to heat treatment, they transform into fine-grained polycrystalline materials known as glass-ceramics. This transition is due to controlled crystallization, which shifts them to a lower energy crystalline state. Notably, the mechanical attributes of glass-ceramics are superior to that of the original glass. Additionally, glass-ceramics may showcase other distinct properties beneficial for specific applications in fields such as construction, optics, and medicine, among others (Fu et al., 2020; Rawlings et al., 2006).

For example, in the case of clay-based ceramics, the natural raw materials used to manufacture them exhibit a vast range of compositional variations, resulting in highly diverse products, such as crucibles and refractory bricks (Figueirêdo et al., 2019). Consequently, these products can withstand additional compositional fluctuations and raw material alterations, which means that various kinds of waste, such as recycled glass cullet, can be integrated into the internal structure of ceramic tiles (Andreola et al., 2016). Darweesh (2019) conducted a study on the usage of glass waste nanoparticles with a ceramic mixture to make floor and wall tiles. Through experiments, it was found that adding up to 25 wt% glass resulted in improvements in the mechanical, physical, and thermal properties of the tiles, in addition to their microstructure, when fired at 1150 °C. However, using more than 25% glass had negative impacts on the mechanical and physical features of the final product, as well as its appearance. While firing shrinkage rose with both glass content and temperature, dry shrinkage remained constant. As the proportion of glass increased, the linear thermal expansion coefficient decreased. Andreola et al. (2010) substituted the traditional ceramic tile components with clean/milled CRT waste. They maintained the clay ratio constant while adding panel glass up to 20 wt% and carrying out the sintering process at 1210 °C. Their findings showed that the resulting specimens possessed characteristics resembling those of widely available ceramic floor and wall tiles. This demonstrated that panel glass may be recycled and used in ceramic formulations.

This approach shares common challenges and limitations with other strategies, including.

- Processing challenges: Integrating glass waste requires adjustments in processing conditions like firing temperatures and durations to ensure desirable final product properties. This necessitates precise control to fully integrate the glass waste without compromising the product's durability and appearance (Gol et al., 2021).
- Homogeneity of materials: Glass waste from various sources like LCD panels varies greatly in physicochemical properties from traditional glass, affecting the uniformity and quality of the final products (Cetin, 2023).
- Environmental impact: Although recycling glass waste minimizes landfill use, the process can generate environmental issues such as emissions from high-temperature operations and potential leaching of harmful elements (Almendro-Candel and Jordán Vidal, 2024).
- Scale of application: Scaling up from laboratory to industrial levels presents challenges such as variability in waste glass supply, processing equipment costs, and maintaining consistent quality control (Xin, 2021).

Future research should address these issues to develop this strategy into a sustainable method for managing glass waste.

4.3.1.4. Filters for water/wastewater treatment. Recycling waste glass has potential applications in the filtration techniques used for wastewater and water treatment. Typically, granular media such as gravel, anthracite, and sand are used in these filters to remove contaminants. Sand is typically used as a filter media; however, crushed recycled glass is being examined as an alternative because of its many advantages.

These include the abundance of waste glass, lower backwash rates, a slightly negative charge for effective adsorption of fine particles, lower media costs compared to sand, minimized media blinding and fouling, the ability to pulverize glass into various particle sizes, lower CO_2 emissions from the use of recycled materials in place of nonrenewable ones, and environmental sustainability (Majdinasab and Yuan, 2019a; Salzmann et al., 2022). In a study by Korkosz et al. (2012), two filtration materials, silica sand and glass cullet, were compared to maintain water quality in a swimming pool. The findings suggested that recycled glass could be an effective alternative filtration medium, despite the fact that cullet particles had a larger negative zeta potential. In another study by Soyer et al. (2010), The effectiveness of glass cullet as a fast filter medium was assessed, and the outcomes were contrasted with those of silica sand. The scientists discovered that the efficiency of crushed waste glass and sand filters in eliminating particulates was comparable. However, the use of crushed waste glass significantly reduced head losses. The research also found that if the sand medium was replaced with crushed waste glass with a comparable size distribution, the sand filter's current backwash facilities could be utilized with minimal or no change. Overall, their findings suggested that crushed waste glass, if accessible at a reasonable cost, could be a viable replacement to silica sand in fast filtration.

Despite the benefits of using recycled glass as a filtration medium, future investigations must consider these issues.

- Particle size and sphericity: The shape and size of glass particles can impact filtration effectiveness. Crushed glass typically has lower sphericity than silica sand, altering the filter bed's porosity and hydraulic efficiency, which may affect filtration dynamics (Soyer et al., 2010).
- Chemical stability and leaching: Ion exchange and leaching from the glass can compromise water quality and the long-term stability of the filtration medium (Korkosz et al., 2012).
- Clogging and maintenance: Issues with clogging are common in both sand and crushed glass filters. Sand filters may solidify, decreasing permeability and necessitating media replacement. Glass, while not solidifying, still requires maintenance for material buildup that could hinder water flow and filter efficiency (Salzmann et al., 2022).
- Economic viability: The costs associated with collecting, sorting, and processing glass waste, along with the need for specialized facilities, can make recycled glass less economically viable as a filtration medium (Majdinasab and Yuan, 2019b).
- Regulatory and environmental concerns: Environmental and regulatory standards, which vary regionally, can influence the permissible uses of recycled glass in water filtration, where stringent quality and safety standards apply (Favaro and Ceola, 2021).

While the open-loop strategy offers numerous benefits, there is an urgent need for a more sustainable approach, especially concerning high-quality glass materials. This urgency has compelled society to explore alternative solutions.

4.3.2. *Closed-loop strategy and circular economy*

Though resource reuse and waste recycling are becoming increasingly popular, many locations, both including and excluding environmental protections, still resort to major landfilling and dumping due to traditional linear waste management processes. To address this inefficiency, from the late 1970s, the idea of a circular economy has been gaining traction. The circular economy approach is seen as systemic and collaborative within the sustainability field and is believed to offer radical solutions for a sustainable economy. In the 1970s and 1980s, the notion of a closed-loop economy was first established, and since then, knowledge of circular economy and its possible applications has grown to encompass numerous aspects from multiple disciplines (Brown et al., 2019; Geissdoerfer et al., 2017; Nodehi and Mohamad Taghvaee, 2022b). Sustainability in material use is given top priority in circular economy, which is a conceptual or management approach that breaks down traditional assumptions about the relationship between environmental benefits, economic benefits, and resource recovery. The circular economy is based on the six *Rs*: recover, reduce, remanufacture, redesign, recycle, and reuse, as illustrated in Fig. 4 (Nodehi and Mohamad Taghvaee, 2022b).

Closed-loop recycling has been receiving significant attention lately as it promotes the usage of recycled resources rather than new ones. This method eliminates the issues associated with waste disposal and lowers the need for additional raw materials by utilizing waste from one system as an input for another (Kazmi et al., 2020). When it comes to container glass, Table 2 compares the advantages of closed-loop recycling with the open-loop strategy. This table demonstrates that using a theoretical 100% cullet fraction as opposed to virgin feedstock can reduce CO_2 emissions from the batch melt by 215–250 kgt^{-1}, due to decreased energy use and the elimination of heat interactions with limestone and soda ash. Since glass can be recycled indefinitely, these cost-savings can be realized again and again, subject to how well the recycling regime keeps glass from waste containers in circulation (Butler and Hooper, 2019). However, the implementation of the closed-loop strategy requires new collaborative supply chain configurations to make it practical (Brown et al., 2019).

4.3.2.1. Closed-loop supply chains (CLSC). Currently, the term supply chain refers to a system that integrates facilities and activities to coordinate material procurement, transformation, and distribution of final products to end-users (Hajiaghaei-Keshteli et al., 2019). Managing the supply chain involves designing networks, optimizing the flow of products between different levels, and reducing transport expenses. The network design procedure involves determining the placement of facilities such as plants, distribution centers, and retailers, configuring the network, and satisfying customer requests (Koç, 2017). The goal of a closed-loop supply chain (CLSC) is to maximize value creation over the product's entire life cycle by optimizing its design, control, and operation. By dynamically recovering value over time from varied types and volumes of returns, this is made possible. The primary goal of a CLSC is to extend a product's lifespan or provide it with a second life cycle (Forslund and Björklund, 2022). In the management of CLSC, pricing decisions and waste product recycling have a direct impact on product supply and demand as well as the effectiveness of the supply chain's operation (Ran et al., 2016). As it enables businesses to lessen their adverse environmental effect, the application of CLSC principles is a critical facilitator for sustainability in value-creating networks (Stindt and Sahamie, 2014). Corporate environmental management has shifted from focusing on processes (such as clean technologies) to products, as environmental policies are now more product-oriented. This has two main benefits: it encourages consumers and producers to share roles and responsibilities, and it highlights the fact that environmental costs are not solely a result of production, but also of consumption and post-consumption activities (Blengini et al., 2012). As previously mentioned, despite the growing emphasis on sustainability, some of the most challenging recyclable materials, such as glass, continue to end up in landfills (Carr and Kim, 2017). This is primarily due to the vast variety of glass materials, each of which requires a different approach (Nodehi and Mohamad Taghvaee, 2022b). The creation of value through remanufacturing and recycling is therefore essential for sustainable development. Reverse logistics has emerged as a novel strategy to support businesses in developing sustainable strategies. Research has focused on examining reverse logistics' costs and advantages in order to create cost-benefit optimization models (Ran et al., 2016). To address these concerns, research on sustainability-oriented innovation (SOI) has increasingly emerged in recent years, addressing the topic from various perspectives (Hansen and Große-Dunker, 2012).

In fact, SOI is the implementation of an enhanced or new system, service, or product that provides environmental or social benefits over

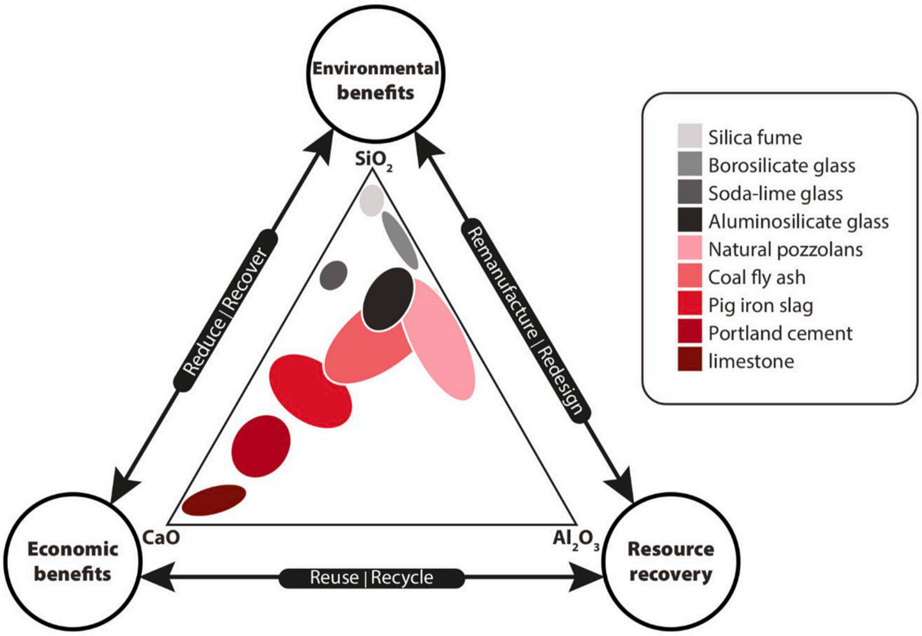

Fig. 4. Recycled glass and circular economy (adapted from (Nodehi and Mohamad Taghvaee, 2022b)).

Table 2
A comparison between container glass recycling via open-loop and closed-loop approaches (Butler and Hooper, 2019).

	Open-Loop	Closed-Loop
End products	Substrate and aggregates	Glass bottles
Secondary energy saving/t (batch melt)	0	1.5 GJ
CO_2 emissions prevention kgt (batch melt)	0	215–250
Maximum cullet proportion	10%–20%	90%

the previous version throughout its life cycle (Hansen and Große-Dunker, 2012). It involves deliberate alterations to an organization's values, practices, and products to create environmental and social value additional to financial gains (Adams et al., 2016). The concept of SOI can be applied to end-of-life value-added CSG sheets used in smartphones. With the help of advanced technologies provided by Industry 4.0 and 5.0 (X. Xu et al., 2021), most of these wastes can be brought back to life by implementing various approaches like reuse and recovery. Before delving into the pertinent technologies, it is imperative to grasp the mechanisms by which CSGs deteriorate over time. Furthermore, it is essential to investigate and familiarize ourselves with techniques that allow for the precise identification and evaluation of their degradation states.

4.4. A smart model for glass circular economy based on the degradation state

The conventional method of recycling glass is effective for most glass products, such as bottles. However, it is not a sustainable solution for high-quality glass sheets. For instance, although the amount of generated smartphone screens waste is much less than building glass, the waste is far more valuable, due to the ion-exchange surface treatment it has undergone. During this process, glasses containing alkalis are submerged in a bath of molten alkali salt like KNO_3, resulting in an ion exchange between the alkali ions in the salt and the ions in the glass. When ions that invade the atomic network of the glass are bigger than the ions already present in the host network, it creates a "stuffing" or "crowding" effect. This effect leads to a high compression stress on the surface and the production of CGS (Fig. 5). This technique can produce high-quality glass components for high-tech applications that require safety and high strength (Connolly, 1989; Datsiou and Overend, 2017; Gy, 2008; L. Jiang et al., 2017; Kang et al., 2020; Marcelli and Poli, 2014; Varshneya, 2010b).

It is obvious that conventional recycling of these waste material streams is a waste of resources, as many of them can be reused with or without some repairs or reconditioning. However, it is crucial to know that all types of glass, especially CSGs, can degrade over time due to weathering and mechanical or physical damage (Gösterişlioğlu et al., 2020). Accordingly, it is vital to understand the degradation mechanisms of glass, how to quantify them, and how this information can be used to make decisions about glass recovery.

In the following, the main factors leading to glass degradation will be discussed. Subsequently, the use of novel technologies that allow for the full characterization of end-of-life CSG sheets will be examined.

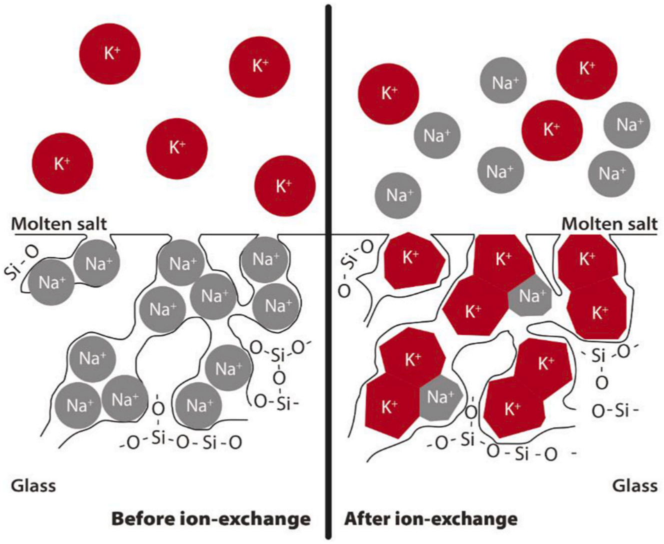

Fig. 5. A schematic of the glass ion-exchanging process (adapted from (Varshneya, 2010a)).

4.4.1. Degradation of CSGs over time

Amorphous silica displays a diverse range in bonding angles and lengths between Oxygen (O) and Silicon (Si). The structure of alkali silicate glasses is a three-dimensional cationic network, where network modifiers like Na^+, K^+, Ca^{2+}, Ba^{2+}, among others, fill any unbalanced gaps. By adding these ions to the glass structure, the integrity of the silicate network is disrupted and expanded, giving rise to nonbridging oxygen (NBO) atoms (Melcher et al., 2010). There are different factors that may lead to glass degradation, including erosion, scratching, temperature changes, airborne pollutants, airborne particulate matter, atmospheric water vapor (relative humidity), ultraviolet (UV) radiation, and static fatigue (Joseph Udi et al., 2023). In this context, the term weathering refers to the deterioration phenomena that glass undergoes over time due to both mechanical and chemical actions. For instance, wind debris or abrasion cause mechanical weathering, whereas environmental factors primarily drive the chemical action for weathering (Majérus et al., 2020).

Glass materials are susceptible to acquiring scratches when they come into contact with materials possessing greater hardness. Scratches are liable to appear during transportation, installation, or while in use. These scratches can be categorized into three distinct regimes (Le Houérou et al., 2003) as shown in Fig. 6; firstly, the micro ductile regime, involving the application of prolonged pressure on the glass surface, ultimately resulting in the formation of underlying cracks. Secondly, the micro-cracking phase is characterized by the emergence of medium-sized cracks in conjunction with longer cracks that link with the glass surface. Lastly, the micro-abrasive regime is defined by the collection of debris or chips on the surface, accompanied by the emergence of minor cracks on the surface. Another contributor to the degradation of glass is erosion, typically stemming from exposure to airborne debris and projectiles. This exposure results in material removal, particularly pronounced during conditions of strong wind. Additionally, stress corrosion is a mechanism leading to the subcritical expansion of micro-cracks and surface imperfections, subsequently causing a decline in the mechanical properties of the glass product over time. Notably, stress corrosion is accelerated under humid conditions. Even at an average global stress level, these micro-cracks tend to propagate gradually, ultimately leading to a prolonged deterioration, referred to as static fatigue (Joseph Udi et al., 2023). In this phenomenon, stress-corrosion cracking is a complex process characterized by the infiltration of reactive molecules, predominantly water, into the crack cavity and the glass network (see Fig. 7). This infiltration results in the gradual breakdown of the glass network and movement of loosely bound alkali ions, a process that is typically slow under normal, unstressed conditions. However, in areas under significant stress, particularly around the crack tip, these processes intensify. This intensification is influenced by specific environmental conditions and the degree of confinement. As the crack tip propagates, these dynamic processes extend outward in concentric layers, especially where the stress exceeds a critical threshold (Benbahouche et al., 2003).

Furthermore, glass weathering culminates in corrosion over time. This corrosion is defined by ion-exchange reactions occurring between the hydrogen-rich species of the corroding medium and the glass's mono- and bivalent network-modifier ions. As a result, these movable cations are drawn out from the glass surface, creating a hydrated or leached layer. Despite this corrosive action, the silicate structure predominantly stays unaltered, a process referred to as "selective leaching" (Gentaz et al., 2011). Factors such as glass composition, temperature, exposure duration, and the corrosive medium's attributes influence the formation rate and thickness of this depleted layer, as well as the degree of glass deterioration. Fig. 8 illustrates a simplified schematic of the glass weathering process. Typically, a water film forms on the glass, due to condensation of air moisture or rain (Fig. 8a). This leads to ion exchange between water film hydrogen species and glass network modifier ions (Fig. 8b). Atmospheric pollutants like SO_2, CO_2, or O_3, along with airborne particulates, can lower the pH of this film, enhancing ion diffusion (Fig. 8c). Temperature increases or humidity decreases can evaporate this film, leading to the formation of crystalline weathering products on the glass (Fig. 8d). The composition of these products is influenced by the glass's composition and atmospheric pollutants (Melcher et al., 2010). It is also important to note that under more severe weathering conditions, the silicon network may undergo alterations.

Reiβ et al. (2019) analyzed the degradation patterns of toughened (both chemical and thermal) and pristine float glass using optical

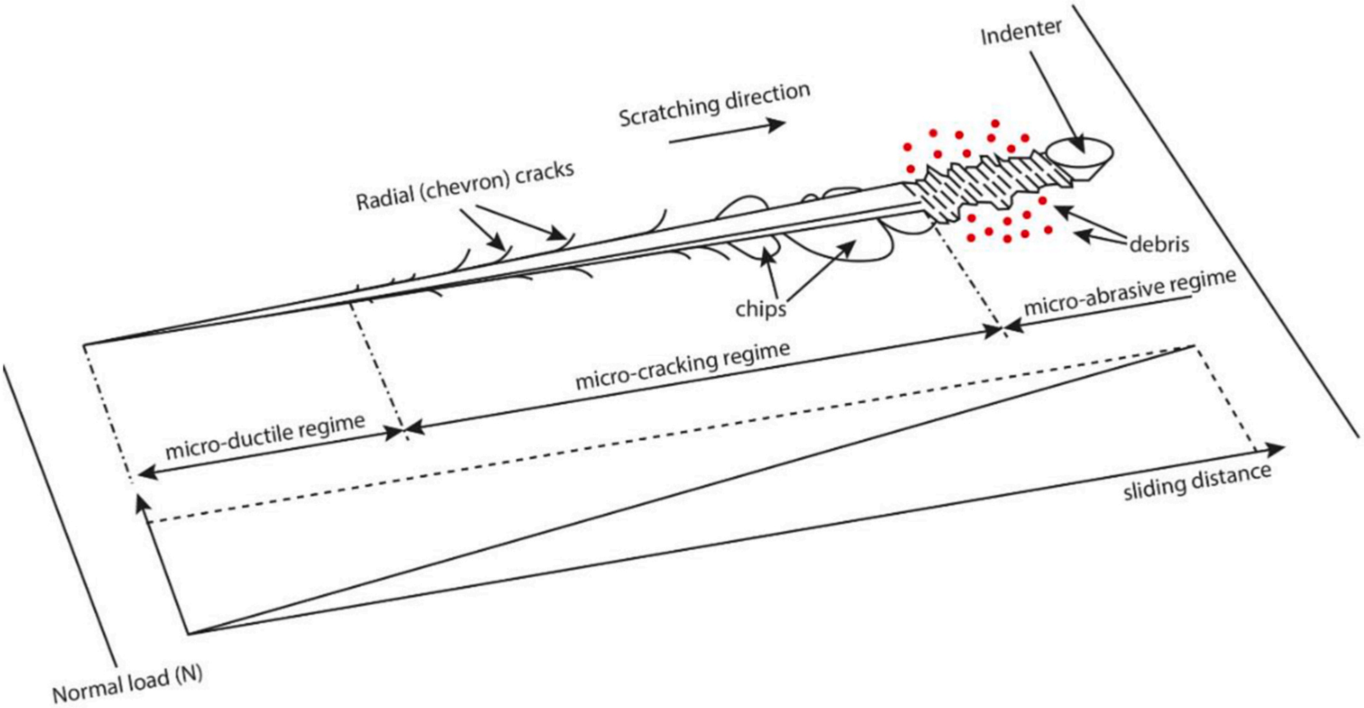

Fig. 6. Scratch pattern on soda-lime silicate glass surface by a Vickers penetrator during a single loading cycle (adapted from (Le Houérou et al., 2003)).

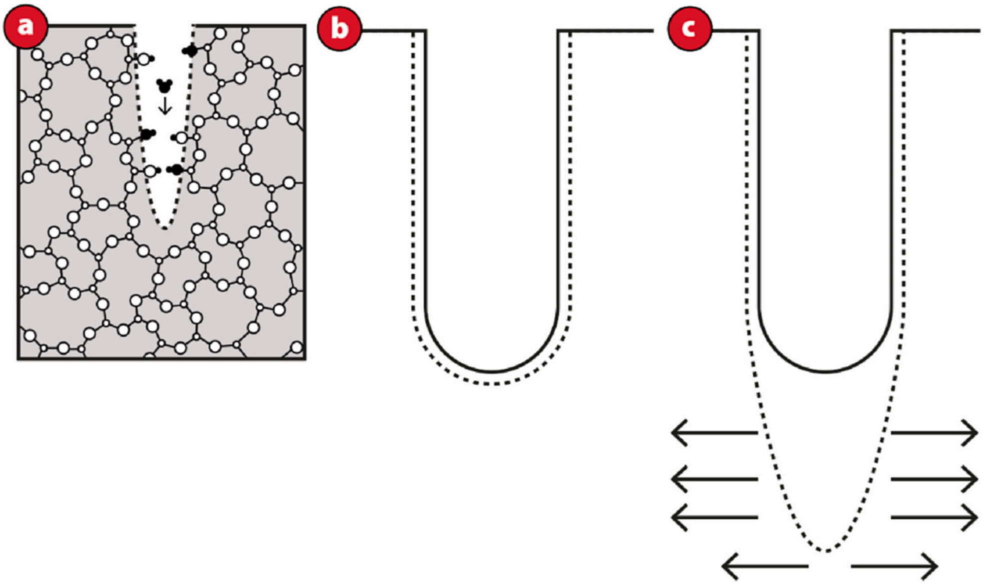

Fig. 7. Static fatigue in glass involves: (a) water-induced cracks in silica, (b) crack growth without stress, and (c) intensified cracking at stress points under tension (adapted from (Benbahouche et al., 2003)).

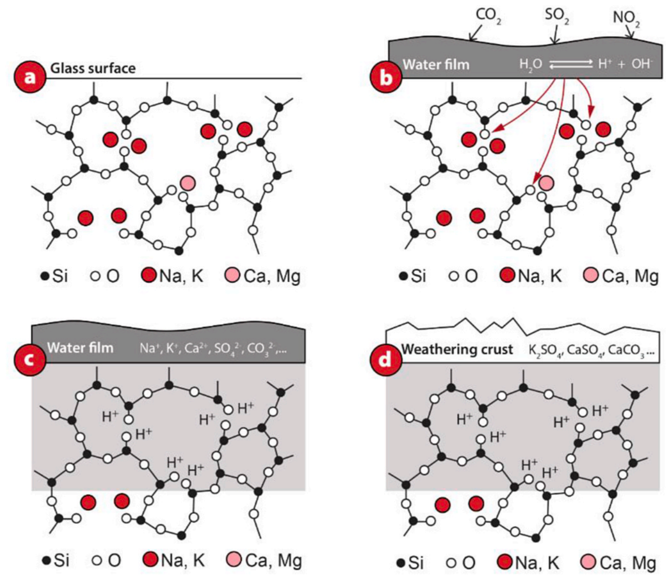

Fig. 8. Simplified glass weathering: (a) clean surface, (b) water film forms with ion exchange and possible acid gas absorption, (c) formation of a hydrogen-rich leached layer, (d) crystalline residues post water evaporation (adapted from (Melcher et al., 2010)).

microscopy, Atomic Force Microscopy (AFM), and X-ray Photoelectron Spectroscopy (XPS). Thermal toughening showed little effect on degradation over seven days of artificial weathering. However, chemical toughening drastically altered corrosion behavior: there was a pronounced lateral change in surface chemistry, but the depth of chemical changes was less compared to tempered and untouched glasses. This is attributed to the integration of larger potassium (K) atoms, which are about 30% bigger than the sodium (Na) atoms they replace in the glass network during strengthening. This reduces the glass network's interstitial sites, thereby limiting the depth of corrosive water attack. In a related study conducted by Gösterişlioğlu et al. (2020), various characterization techniques were employed to investigate the effects of weathering on CSGs. These techniques included White Light Interferometry (WLI) for surface roughness measurements and topography imaging, AFM for detailed surface analysis, Time of Flight Secondary Ion Mass Spectroscopy (TOF-SIMS) for depth profiling, Ultraviolet/Visible/Near-Infrared (UV/VIS/NIR) spectrophotometry for optical transmittance properties, Fourier Transform Infrared (FTIR) spectroscopy for structural changes in the glass network, Differential Surface Refractometry (DSR) for surface compression stress and case depth measuring, and mechanical testing methods like the Vickers hardness test and biaxial bending tests. In line with prior research, it was found that soda-lime silicate glasses, when subjected to the ion exchange process, demonstrate increased corrosion vulnerability upon exposure to weathering conditions. The tendency for corrosion is closely associated with the emergence of alteration layers. Nevertheless, adopting certain measures, such as elevating the alumina content within the glass composition, can effectively diminish this vulnerability.

In summary, current studies indicate that CSGs are susceptible to degradation over their typical lifespan. While there are established methods to evaluate the degradation of glass components, such as smartphone screens, literature lacks models to precisely quantify this state. Moreover, the innovations from Industry 4.0 and 5.0 not only hold promise for introducing real-time assessment techniques and enabling in-depth data analysis but also for determining the potential to recover end-of-life CSGs instead of discarding them as waste. In the subsequent sections, the pivotal roles of these new industrial paradigms that might play a crucial role in this domain are discussed.

4.4.2. Industry 4.0 and its relevant technologies applicable in CSG sheets recovery

The concept of Industry 4.0, which refers to the recent technological advancements in augmented reality, simulation, Additive Manufacturing (AM), autonomous robots, Big Data Analytics (BDA), vertical and horizontal system integration, AI, IoT, M2M communications, cloud computing, and cybersecurity, has recently experienced a rise in popularity and has significant implications for firm sustainability (Bai et al., 2022; Delpla et al., 2022; Rad et al., 2022). These technologies use the internet and other related technologies to integrate processes, production lines, intelligent machines, human actors, and physical objects across organizational boundaries to build a new agile, interconnected, and intelligent value chain (Bai et al., 2023; Gong et al., 2022; Schumacher et al., 2016; Taddei et al., 2022). This real-time information exchange throughout supply chains improves their visibility and encourages both horizontal and vertical integration (Sharma et al., 2023). A schematic history of the various industrial revolutions, along with the major Information and Communication Technology (ICT) enablers for Industry 4.0 and 0.5, is depicted in Fig. 9. The concept of Industry 5.0 and its role in this paradigm shift is elaborated in Section 4.4.3.

The importance of sustainability has been recognized in today's industrial landscape, with measures already underway to achieve it, due to the increasing population and demands (Malik et al., 2022). In the following, Industry 4.0 technologies applicable for supply chain management of end-of-life smartphone screen will be reviewed and evaluated on their suitability for this task.

4.4.2.1. Artificial intelligence (AI) for glass material defect detection. In the field of material science, AI serves as a versatile tool that handles a wide range of tasks, from basic procedures to intricate analyses (DeCost et al., 2020). AI is instrumental in deciphering data, performing image and spectral assessments, and proves particularly valuable in specialized areas such as X-ray tomography for battery material studies. Furthermore, Machine Learning (ML) algorithms find application in various diffraction methods — including X-ray, neutron, and electron diffraction — to achieve 3D crystallographic characterization with spatial resolution (Chan et al., 2020). These algorithms enable efficient processing of large data sets, significantly enhancing the throughput of data analysis. In addition to these applications, AI also facilitates the complex endeavor of phase diagram mapping, offering an approach that is both more efficient and precise than traditional rule-based data analysis methods (López, 2023). AI and ML algorithms excel at rapidly parsing large, multi-source scientific data sets. They are adept at identifying complicated, nonlinear relationships within the data, thereby predicting material properties—such as corrosion rates (Hakimian et al., 2023), tensile strength (Z. Liu and Wang, 2023), and wear characteristics (Kruthiventi and Ammisetti, 2023)—with high accuracy. These computational models are capable of managing large-scale data and come with additional benefits such as noise resilience and fault tolerance (Torres-Huitzil and Girau, 2017). This makes them exceptionally effective in forecasting how materials will behave under varying environmental conditions. When AI methodologies are integrated with other computational techniques, the result is a more robust and efficient system for material characterization (Chibani and Coudert, 2020). Advances in these domains are anticipated to eventually pave the way for fully autonomous material characterization systems (Dimiduk et al., 2018).

Within the scope of this review study, AI and ML methodologies are employed to evaluate traditional characterization data sourced from a variety of techniques and from different CGSs operating under diverse conditions. This aids in deriving a dependable model to forecast the degradation state of smartphone screens in everyday use. Information from various sensors or satellites enables an accurate assessment of the weathering history of these glass components. This essentially implies that there is no necessity for costly and lengthy traditional characterization processes to determine the current degradation state of a smartphone screen. While elements like temperature, humidity, and UV exposure can influence the mechanical, physical, and chemical attributes of a smartphone screen, the potential for damages resulting from accidents is a factor that warrants attention.

The majority of current smartphones rely on touchscreens that occupy a significant portion of the device's front panel. This means that the risk of damage to the screen is higher when the phone is dropped, resulting in a greater number of broken smartphones (Schaub et al., 2014). Fortunately, advances in AI technology have made it possible to individually examine each discarded smartphone screen for surface defects and determine its potential for reuse. While most AI technologies for inspecting smartphone screens are designed for use on new screens during production, they can also be applied to waste screens.

Liu et al. (2011) proposed a Multi-Resolution and Information Fusion (MRIF) technique for smartphone screen defect detection. At the decision level, the study's main objective was to categorize five different categories of glass defects. As illustrated in Fig. 10, the identifying process entails first getting a subtracting image by applying a downward threshold technique to the real-time detected image, and then employing twice Otsu's thresholding algorithm (Sankur, 2004) to identify the correct defect region inside the subtracting image. Ten statistical features are then recovered from the estimated sub-images at each scale after performing a three-level decomposition of the region using Daubechies 4 (db4) wavelet. The smartphone screen defects are classified at each level of decomposition using four classifiers, which are based on

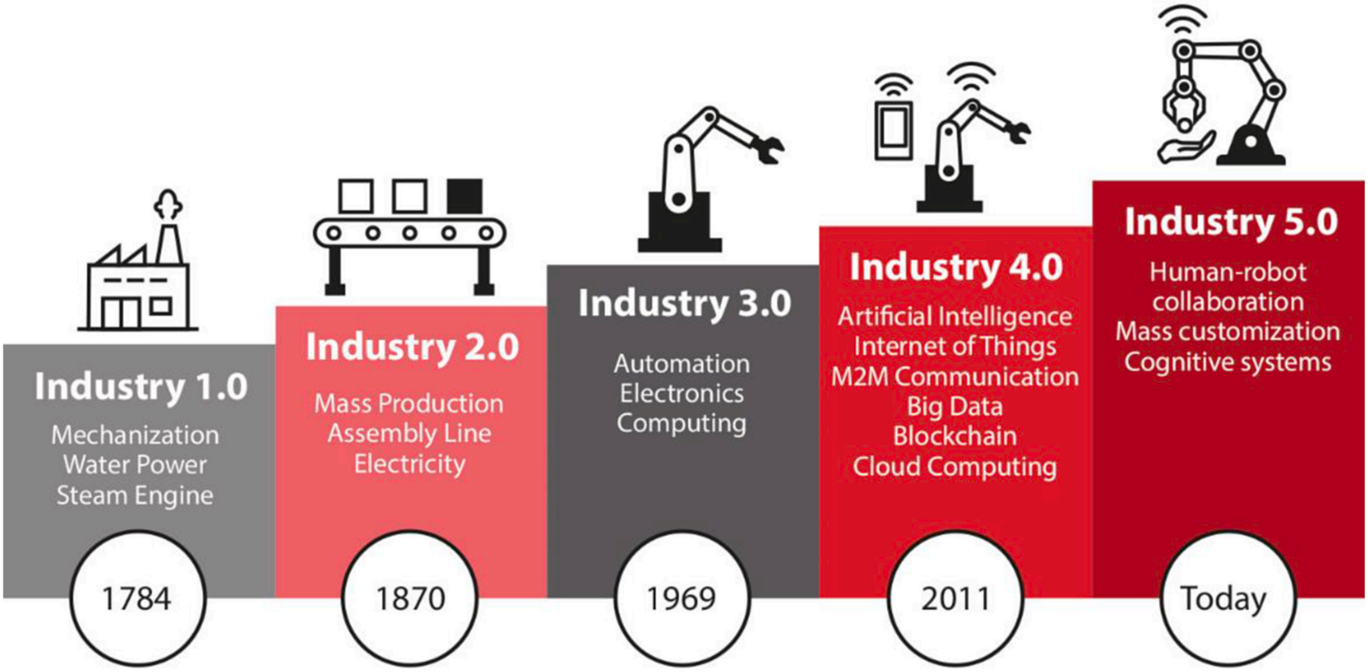

Fig. 9. Principal enablers of each industrial revolution leading up to Industry 5.0.

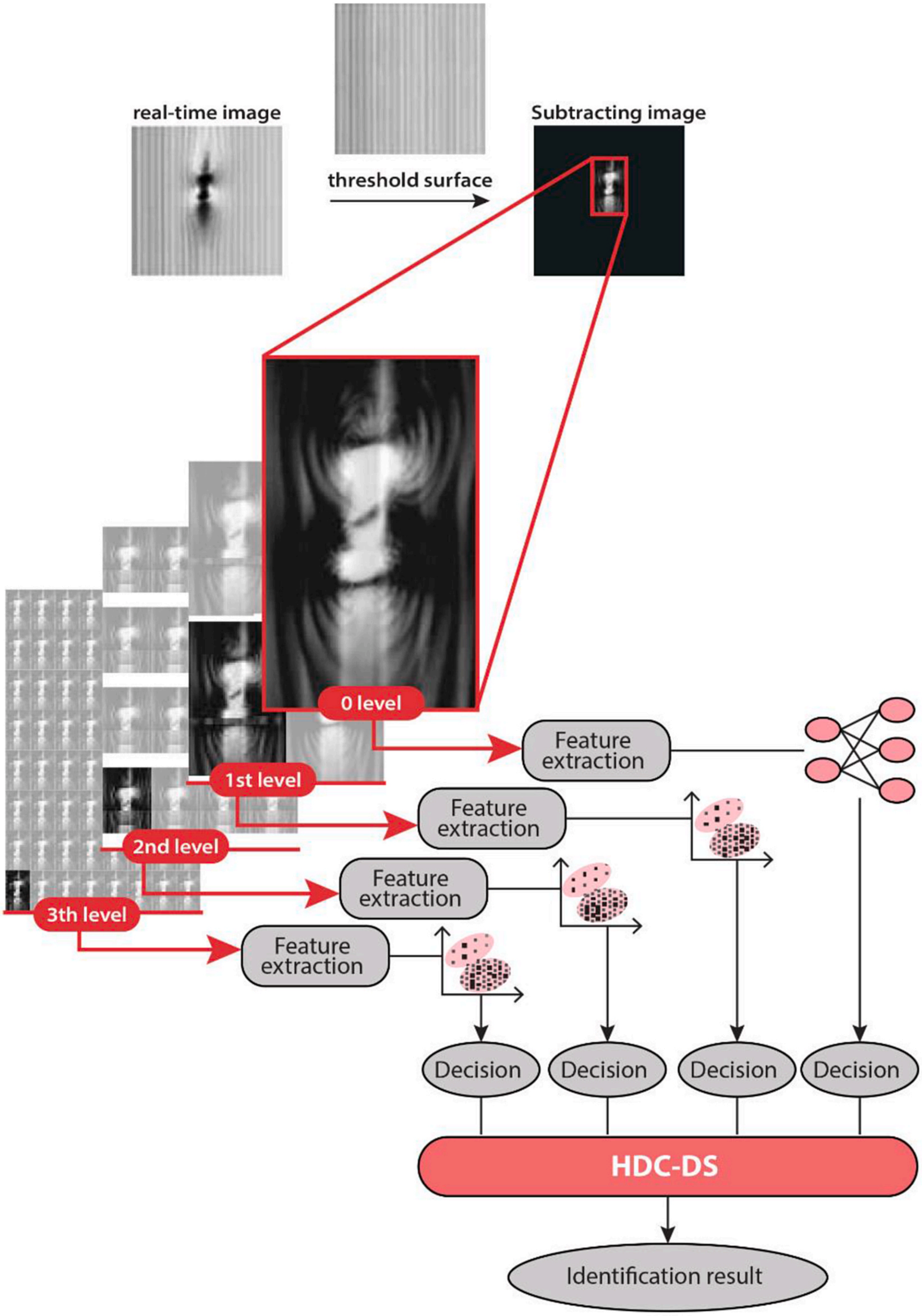

Fig. 10. The smartphone screen defect detection system based on MRIF (adapted from (H. Liu et al., 2011)).

Fuzzy K-Nearest Neighbor (FKNN) and Artificial Neural Network (ANN). As an improved version of Dempster-Shafer (DS) evidence theory, the Head Difference Calibration (HDC)-DS approach, is then utilized to combine the identification results. The HDC-DS fusion method performs better than the normal DS evidence theory. For inclusions and bubbles, the ten retrieved features have clear representativeness, but there are still conflicting results for cracks. To explore more efficient feature extraction for cracks, more research is required.

In another study, Zhao et al. (2011) presented a novel method for the detection and identification of glass flaws in low-resolution images (Fig. 11). Initially, the Canny edge detection approach is used to pinpoint the region of the defect, enabling the identification of the smallest connected area (rectangle). A specific filter is employed to acquire binary information from the core region, which is then subjected to noise reduction. To specify the characteristics of the glass defect, the researchers proposed a Binary Feature Histogram (BFH). The AdaBoost algorithm is then used to classify data. The recognition accuracy for bubbles is higher than that of non-bubbles, which may be due to the

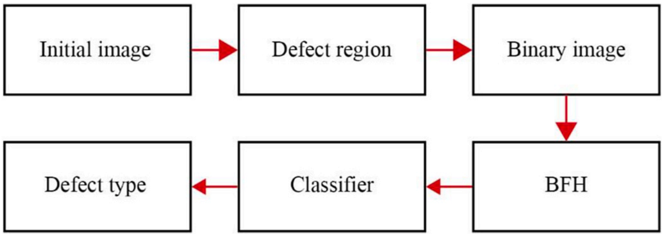

Fig. 11. The flow chart of the defect detection algorithm using BFH (adapted from (Zhao et al., 2011).

smaller sample size of non-bubble cases and their greater complexity compared to bubble cases. This technique has an accuracy rate of 91.6%.

Yuan et al. (2018) introduced a new instrument for detecting defects in smartphone screens that uses a backlight line-scanning imaging method. To detect defects, they employed a dilated segmentation network method and utilized Generative Adversarial Networks (GANs) as the training networks. As the need for a substantial training data is a drawback, they provided a data generation process consisting of two steps: data augmentation and defect superposition. Finally, they collected considerable manually labeled real images to validate the suggested detection technique. Fig. 12 depicts a condensed general perspective of the defect segmentation model training with the adversarial network. The experimental findings demonstrated the effectiveness of the proposed method in detecting defects in smartphone screens. However, applying unsupervised deep learning techniques to create synthetic images with annotations willstill require more research and development.

Jin et al. (2019) suggested an approach for training a Convolutional Neural Network (CNN) through an autoencoder. They used a Convolutional Autoencoder (CAE) to pre-train the convolution kernel, which reduced training time that would be required if the kernel was randomly initialized. A Fuzzy Support Vector Machine (FSVM) was used in place of the Softmax classifier to classify glass defects in order to address the over-fitting issue brought on by the small sample size of glass defect data. To solve problems with inclusions and tumors type defects being mistakenly identified due to minute variations in the feature space, they also devised a multi-channel auto-encoding CNN model. The Multi-Channel Auto-Encoding Convolutional Neural Network (MCAECNN) system they developed achieved an overall recognition accuracy rate of 97% (Fig. 13).

Park et al. (2020) established a defect inspection system for smartphone screen using a Deep-Learning Neural Network (DLNN). The structure utilized in this system combines data from various imaging inspection tools and is capable of analyzing images captured in both dark-field and bright-field. Four classes of data, including Vertical Bright-Field Image (VBFI), Horizontal Dark-Field Image (HDFI), Vertical Dark-Field Image (VDFI), and Horizontal Bright-Field Image (HBFI) are included in the bright-field and dark-field imaging. The entire process of the smartphone screen defect detection system is demonstrated in Fig. 14. This inspection system achieves a defect detection accuracy rate of up to 99%.

Finally, Jiang et al. (2020) developed a system for detecting surface defects on screen-printed mobile phone back glass. To find significant flaws like dents, scratches, and discolorations, they used a double bright-field imaging system made up of Low-Angle Bright-Field (LABF) and Coaxial Bright-Field (CBF) imaging systems. To segment the images, they used a symmetric CNN, which was trained on over 30,000 manually annotated images. The Symmetry-Net achieved an average precision and recall of over 91% and 95%, respectively, for all types of defects, as verified by the test experiment. This approach's performance is superior to that of conventional approaches, and it can be used to find flaws in a particular image. Although more study is required to improve the recognition accuracy with fewer samples and boost computing efficiency, the system has significant potential for other surface inspection tasks.

From the reviewed literature, AI-based techniques have significantly advanced, proving to be reliable for surface detection in glass sheets. Primarily designed for factory quality control, these methods are also suitable for end-of-life smartphone screen inspections. Additionally, similar systems could analyze data on glass' chemical degradation. While current literature does not yet address this potential, AI holds promise in this domain. Once equipped with necessary data, an intelligent system can determine the glass' suitability for reuse or recovery in order to integrate such material flows in a circular economy approach. This decision-making process is enhanced by M2M communications and IoT technologies under the Industry 4.0 framework, where machines can potentially collaborate to determine an end-of-life smartphone screen's recovery level. Section 4.4.2.2 delves deeper into these technologies.

4.4.2.2. M2M communications and IoT. Industry 4.0 heavily depends on M2M communication, which enables devices to exchange information with each other autonomously, without human intervention (Varghese and Tandur, 2014). This covers a wide range of devices, including laptops, smartphones, tablets, robots, automatic sensors, and factory equipment. This makes it possible for these devices to react to external feedback and modify their internal operations accordingly. M2M is a critical technology that enables future Industrial Internet of Things (IIoT) applications (Laghari et al., 2021; Meng et al., 2017). The IIoT enables the entire process of order execution, production, implementation, and product delivery to be completed without any human intervention (Kilani et al., 2020; Ślusarczyk, 2018). To achieve this, digital technologies are utilized to enhance technical systems, making them

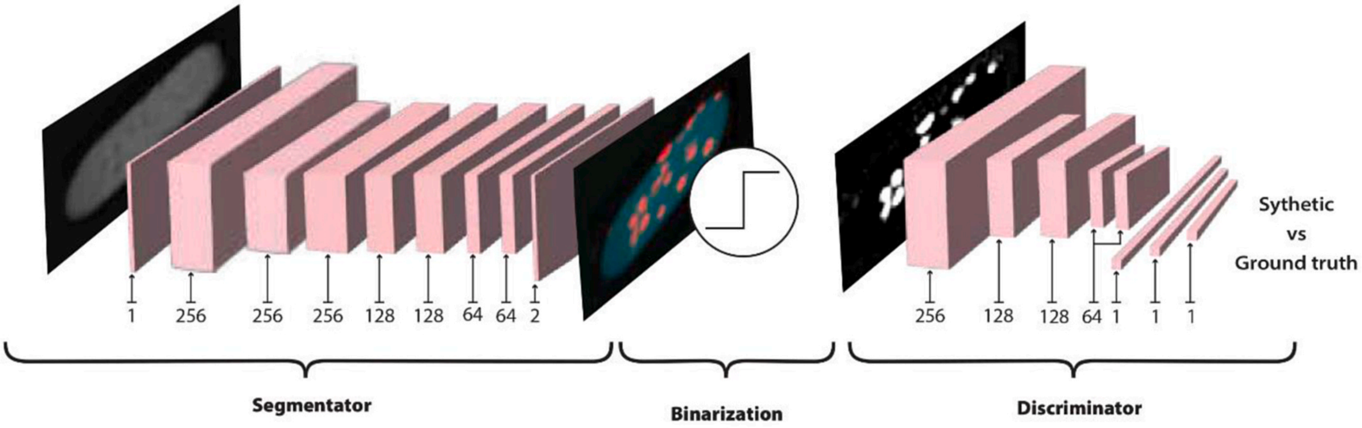

Fig. 12. The design of the adversarial network training defect segmentation model (adapted from (Z.-C. Yuan et al., 2018)).

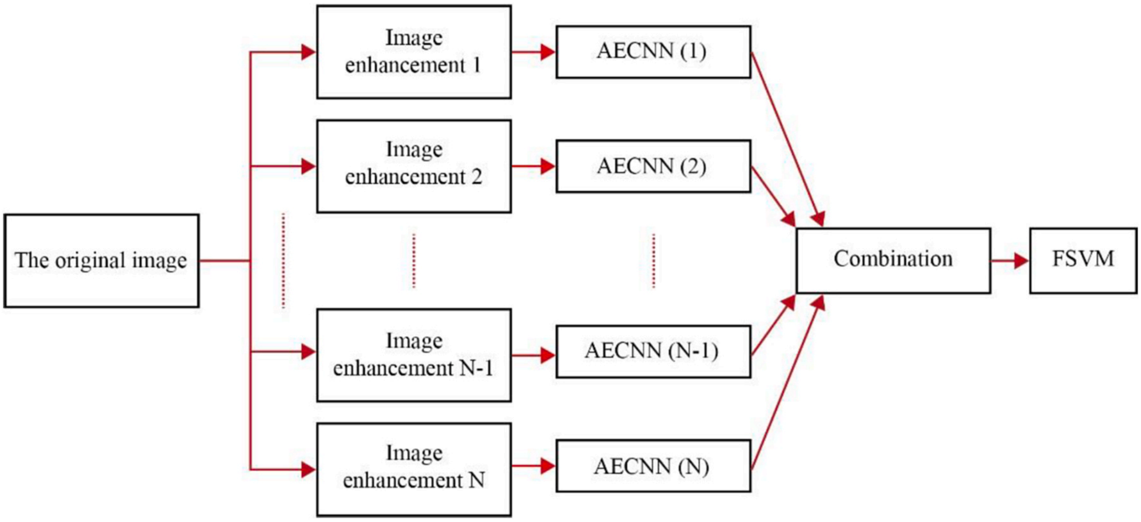

Fig. 13. The architecture of the MCAECNN system (adapted from (Jin et al., 2019)).

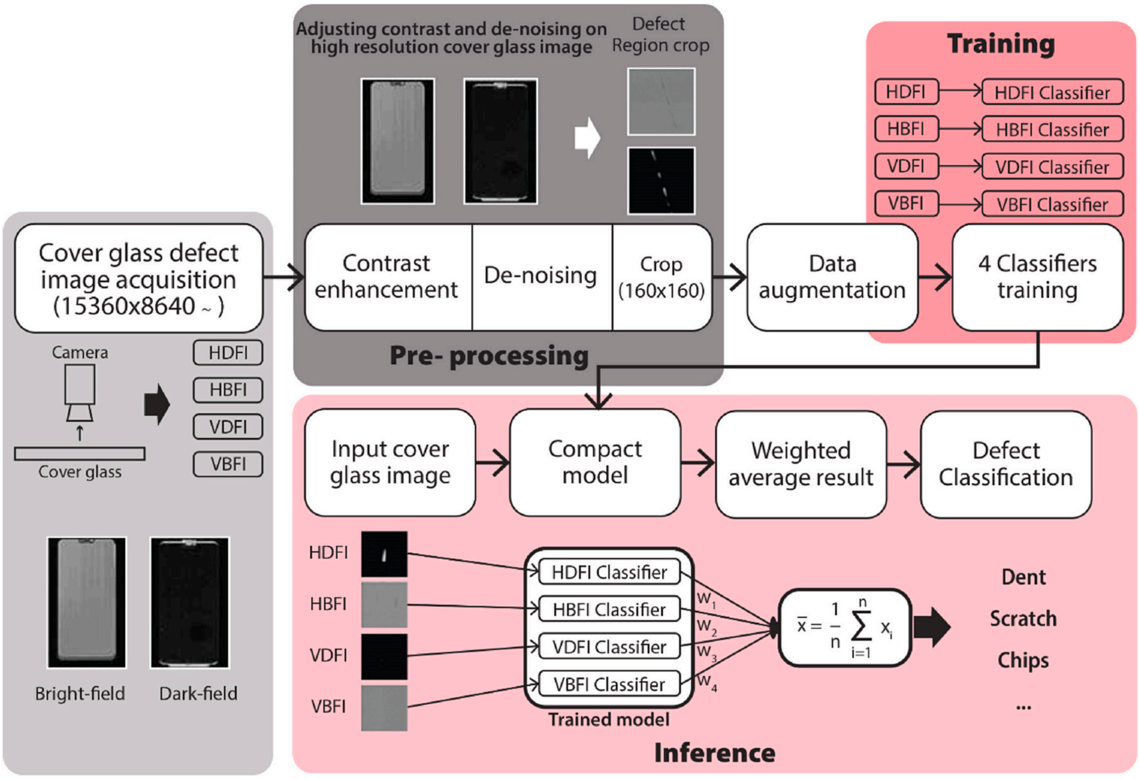

Fig. 14. The flowchart of the smartphone screen defect detection system based on DLNN (adapted from (Park et al., 2020)).

interconnected and intelligent. The IoT is composed of engineered systems - Cyber-Physical Systems (CPS) - that communicate with each other. These systems use BDA to make informed decisions locally and autonomously (Hahn, 2019). These technologies have enabled the achievement of circular economy for many end-of-life wastes, such as smartphone screens, which was previously impossible. Researchers across the globe are working towards advancing this industrial revolution and adapting it to promote circular economy in their respective countries (Cavalieri et al., 2021; Fraga-Lamas et al., 2021; Lopes de Sousa Jabbour et al., 2018).

The central concept is the development of smart factories as an innovative manufacturing strategy. These factories use the IoT to connect production units to one another, resulting in increased productivity, quicker adaptation to new designs, and higher flexibility. The production of on-demand, economically feasible batch-size 1 products is possible in these smart factories. As a result, all expenses that are not necessary for producing the final products must be eliminated. In this context, advanced remanufacturing technologies can be utilized to convert damaged glass sheets into new products in a cost-effective and sustainable manner, particularly for end-of-life smartphone screens. These remanufacturing technologies must be adaptable and suitable for mass personalization, which will be explained in the following section.

4.4.2.3. Remanufacturing technologies. Remanufacturing is crucial to a circular economy because it allows for the reuse of old, broken product components through a number of processes, including disassembling old products, cleaning, restoring, assembling, testing, storing, and packaging (Kerin and Pham, 2019). Indeed, increased resource efficiency, decreased waste, and cleaner, more sustainable production are all possible outcomes of product remanufacturing. In different fields, "remanufacturing" may have slightly different meanings. It is widely acknowledged, however, that remanufacturing is the process by which a used product is transformed into a brand-new one that meets or exceeds the standards of new products in terms of both warranty and performance (Bag et al., 2019; Kerin and Pham, 2019).

There are multiple techniques for glass remanufacturing (polishing, cutting, milling, and drilling), which can be divided into four types; thermal (e.g. laser machining), mechanical (e.g. Abrasive Slurry Jet Machining (ASJM), Abrasive Water Jet Machining (AWJM), Abrasive Jet Micromachining (AJM), and ultrasonic drilling), chemical (e.g. including Deep Reactive Ion Etching (DRIE), and plasma etching) and hybrid processes (such as Laser-Induced Plasma Micromachining (LIPMM), water-assisted micromachining, vibration-assisted micromachining, and Spark-Assisted Chemical Engraving (SACE)) with each their own benefits and constraints on machining (L. Hof and Abou Ziki, 2017). For instance, SACE is one of the few production methods that can do several operations using the same setup while also significantly reducing calibration-related issues (L. A. Hof and Wuthrich, 2021; Villeneuve and Hof, 2023).

The potential of various glass remanufacturing procedures to generate new, customized parts from end-of-life smartphone screens requires careful investigation. Disassembly challenges, particularly due to adhesives used in smartphone assembly (Ueda et al., 2024), must be addressed. Moreover, when removing the touchscreen component, typically composed of indium tin oxide (ITO), from screen glass, consideration should be given to the hazardous nature of ITO (Bomhard and Ernst, 2016). Despite these complexities, Industry 4.0's emphasis on flexible manufacturing techniques and cost reduction could enable the production of personalized products from this recycled material at a reasonable price (L. A. Hof and Wüthrich, 2018).

While Industry 4.0 offers numerous benefits, concerns arise about the long-term role of humans, paving the way for the emergence of Industry 5.0. In the subsequent sections (4.4.3 and 4.4.4), the exploration will focus on how the next industrial revolution may influence this paradigm shift.

4.4.3. Industry 5.0 and its potential role in this paradigm shift

Industry 5.0 seeks to merge the subjective intelligence of humans with the efficiency and precision of machines, enhanced by artificial intelligence. This fusion emphasizes the importance of humanistic consideration, steering industrial production towards a harmonious and symbiotic ecosystem. With its innovative perspective, it aims to bridge the gap between manufacturing and societal demands, transitioning from a focus on technology to a value-centric approach (Leng et al., 2022; X. Xu et al., 2021). Industry 5.0 emphasizes the incorporation of human elements when introducing new technologies into industrial systems. This approach fosters a tight-knit collaboration between human workers and machines, leveraging human ingenuity to enhance efficiency by merging workflows with smart systems (Nahavandi, 2019).

With having various key enablers such as, big data analytics, Internet of Everything (IoE), 6G networks and beyond, blockchain, digital twins, Cobots, edge/cloud computing, etc., various areas like manufacturing products, cloud manufacturing, intelligent healthcare, and supply chain management can benefit significantly from the role of Industry 5.0 (Maddikunta et al., 2022; Mejía-Moncayo et al., 2023).

Within the scope of this paper, by integrating traceability, circularity, and waste reduction measures, Industry 5.0 can enhance supply chain management and circular economy across multiple facets of the supply chain including raw materials, production, transportation, distribution, and recycling. To be more precise, advanced tracking, IoT sensors, and optimization algorithms can support closed-loop material flows, remanufacturing, and waste reduction. Furthermore, Industry 5.0 technologies can be adopted to enhance cross-sectoral supply chain resilience, ensuring a more robust and adaptable supply chain that can withstand disruptions and changes (Barata and Kayser, 2023). The collaboration of humans and machines in Industry 5.0 not only results in a highly efficient and value-added supply chain, but it can lead to emergence of new professions such as, such as supply chain network designers, supply chain analysts, industrial engineers, and data analysts specializing in assisting supply chains in complex, uncertain, and dynamic environments (Modgil et al., 2023).

In brief, Industry 5.0 leverages advanced technologies to design intelligent products that can track their lifecycle, fitting seamlessly into a circular economy and enhancing operational efficiency, economic growth, and environmental sustainability (Ghobakhloo et al., 2022). These products provide real-time data for dynamic life cycle assessments (Mejía-Moncayo et al., 2023), enabling more comprehensive evaluations and smarter maintenance decisions (Javaid and Haleem, 2020; Pizoń and Gola, 2023). Moreover, Industry 5.0 combines human creativity with automation, such as collaborative robots, to improve recycling and remanufacturing processes, thus maintaining ethical standards and achieving ambitious recycling targets (Turner et al., 2022).

4.4.4. An advanced intelligent model for smartphone screen recovery: a conceptual approach

Based on the reviewed literature and its evaluation, the present study concludes with a proposed model that covers a series of steps ranging from data collection to a feedback mechanism for smartphone screen recovery. This model is depicted graphically in Fig. 15. Although the model is primarily conceptual, it holds practical promise, especially when integrated with enhanced sensors, readily available in smart devices, such as smartphones. Such sensors might also offer multifunctional utility, thereby augmenting the capabilities of contemporary smartphones.

4.4.4.1. Data collection. The data essential for the proposed model can be sourced from conventional characterization techniques. Alternatively, a suite of sensors can be integrated into smartphones, capturing environmental conditions that could predict the degradation state of the glass. These might include sensors monitoring temperature, relative humidity, and UV radiation levels. Satellite information, based on the device's location, can further complement this data collection. On the topic of physical damage, the introduction of piezoelectric sensors can effectively register alterations in the glass's physical condition, identifying concerns like micro-cracks or pronounced fissures.

4.4.4.2. Data preprocessing. Upon data acquisition, pivotal features must be distilled from the raw data, such as the progression rate of cracks or the cumulative UV exposure over a given period. Image processing techniques might prove invaluable here, particularly in amplifying the clarity of images for superior crack detection.

4.4.4.3. Data analysis. Once processed, the data can be subjected to a hybrid analytical approach, utilizing time series models for sensor-acquired data and CNNs for imaging. The end goal would be a categorization of the degradation state, potentially on a scale of 1–10.

4.4.4.4. Feedback loop. The AI system should be dynamic, adapting and refining its predictions as fresh data streams in. The continuous influx of data from myriad smartphones will only enhance the model's precision.

4.4.4.5. Decision-making. From the analyzed degradation state, the AI based algorithm, informed by insights from the concept of Circular Manufacturing 4.0 –a system focused on extending product life cycles and closing material loops through maintenance, reuse, and remanufacturing of products (Mejía-Moncayo et al., 2023)– and the integration

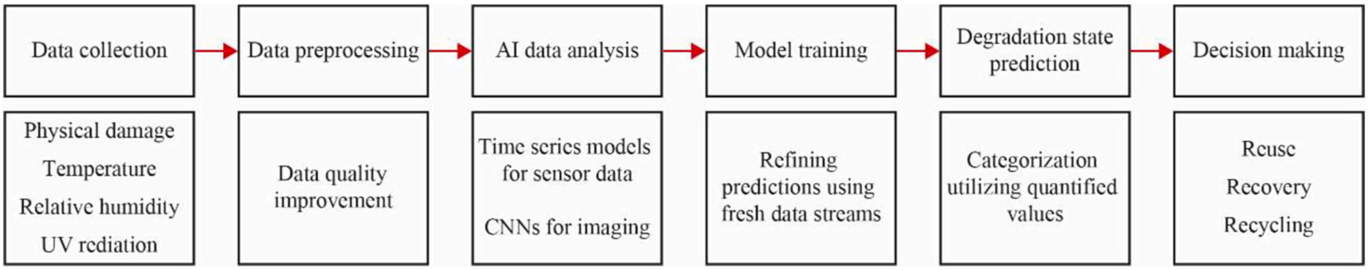

Fig. 15. A conceptual framework for the recovery of smartphone screens.

of the IoT in CLSC, can suggest potential strategies for the recovery of smartphone screens (Fig. 16) (Delpla et al., 2022).

- *Reuse*: Suitable for slightly degraded smartphone glass still viable for its primary function. The addition of IoT and embedded sensors can enhance the capability of AI in monitoring real-time conditions of smartphone glass, ensuring that the decision to reuse is based on accurate and current data regarding its structural integrity and functional viability. This enhanced monitoring allows for more effective and efficient reuse, ensuring materials are utilized to their fullest potential before proceeding to other forms of recovery.
- *Recovery*: For minor damages or limited major damages rectifiable through techniques like remanufacturing. The discussion on advanced recovery processes, including remanufacturing techniques informed by Industry 4.0 and 5.0 technologies, can be adapted here. This approach can provide nuanced recovery options, employing data-driven decision-making to optimize the process. By evaluating the economic and environmental impacts of different recovery strategies, AI can recommend the most cost-effective and environmentally friendly method for glass recovery.
- *Recycling*: For instances where the smartphone glass is irreparably damaged. Integrating the principles of Circular Manufacturing 4.0, AI can optimize the recycling process. This involves not only determining when recycling is the most suitable option but also ensuring that the process aligns with sustainability goals and maximizes resource efficiency. The incorporation of IoT data can aid in categorizing end-of-life smartphone glasses based on their suitability for recycling, while considering the overall environmental and economic impacts of this strategy.

By incorporating these advanced technologies and methodologies, the AI system becomes more than just a tool for identifying degradation states; it transforms into an intelligent decision-maker that optimizes the lifecycle management of smartphone glass products, aligning with the principles of sustainability and efficiency.

Such intelligent model could seamlessly be embedded within the smartphone's OS or presented as a standalone application. Users could receive periodic prompts to assess their smartphone screen, or such assessments could be auto-scheduled during phone downtimes. User feedback will play a pivotal role in gauging the AI's prediction accuracy.

However, several challenges loom. The heterogeneity in smartphone models, each boasting unique smartphone screen and sensor configurations, could pose data consistency challenges. Moreover, present-day smartphones may lack dedicated sensors for discerning glass degradation, necessitating specialized sensors in future models. On the brighter side, the proposed approach could potentially prolong the smartphone screen's lifespan by consistently monitoring and addressing its degradation. By promoting recovery or reuse over immediate discarding, it also stands as a sustainable solution, reducing electronic waste.

In summary, while certain challenges might impede the smooth integration of such proposed system, its potential contributions to sustainability and lifespan enhancement are too significant to overlook.

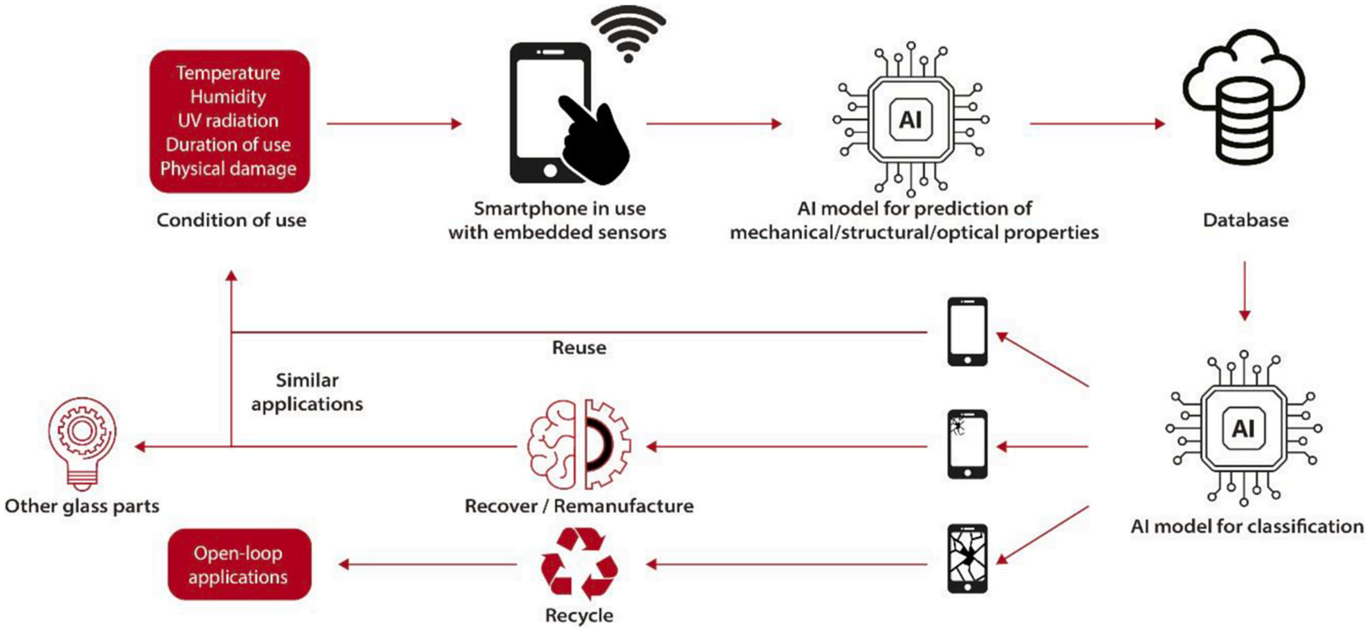

Fig. 16. A conceptual framework for the recovery of smartphone screens.

5. Conclusion and outlook

Glass is a material that is widely used due to its transparency and brittleness. With the increased usage of glass items, there is now a significant amount of waste glass. Landfilling and incineration are not effective waste management options as they result in a waste of resources and energy. Therefore, recycling and waste reduction are essential components of a waste management system. While container glass is widely recycled, other types of glass waste are typically downcycled or disposed of in landfills because there is a lack of infrastructure for collecting and separating them based on their composition and potential reuse applications. This problem is further complicated by the use of high-quality glass sheets with post-processing treatments, such as CSG, in devices such as smartphones.

Today, advanced technologies associated with Industry 4.0, such as AI, M2M communication, IoT, advanced remanufacturing technologies, Cobots, and intelligent products have made it possible to characterize and remanufacture end-of-life smartphone screens for the original or alternative high-tech applications in smart factories. AI technologies can be used to inspect individual waste smartphone screens for surface defects and decide whether to remanufacture them for other high-tech applications. M2M communications and IoT technologies link the characterization unit to machines used for remanufacturing. The low-cost machining setup and mass-personalization capabilities of some manufacturing techniques, such as SACE, make them ideal for remanufacturing end-of-life smartphone screens and transforming them into a wide variety of other high-value glass items. This approach enables on-demand production of economically feasible batch-size 1 products, and represents a paradigm shift from conventional recycling methods for high-quality glass sheets to a sustainable solution.

Despite the fact that some of these technologies are currently being used at an industrial level and are considered mature, further research is required to determine their feasibility and economic costs. The lack of a proper logistics system for managing end-of-life smartphone screens is currently the most significant challenge to the approach. Additionally, the diverse nature of these wastes necessitates the use of AI-based characterization methods and remanufacturing techniques to achieve accurate results. However, if these challenges can be overcome, a sustainable solution for recovering smartphone screen waste and transforming it into valuable products will be possible.

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CRediT authorship contribution statement

Seyed Ali Delbari: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucas A. Hof:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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