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The Role of Recycled Glass in Optical Fiber Technology for Circular Economies: A Review

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ABSTRACT
The growing demand for sustainable requirements in all disciplines that should be aligned with the concept of smart cities with parallel of the need to achieve the united nation sustainable development goals by 2030, leads the researchers to find innovative solution in circular economy based. One of the new technologies that have wide range of application due to its variety of application is the Glass optical Fibers. Optical Fibers have a contribution to different industries such communication, construction and manufacturing. This led to a huge quantity of waste based on the linear economy concept. This research focus on highlighting the contribution of recycled glass as a sustainable alternative to virgin silica, emphasizing its ability to retain essential properties. Furthermore, the adoption of recycled glass aligns with circular economy principles, enabling resource conservation, reduced environmental degradation, and energy-efficient manufacturing. The research also highlighted the challenging for recycling the optical Fiber-based glass. By addressing these challenges, recycled glass optical fibres contribute significantly to achieving multiple Sustainable Development Goals (SDGs). Moreover, the critical role of recycled glass in fostering eco-friendly and technologically advanced smart city infrastructures while promoting sustainability, efficiency, and environmental stewardship in modern urban development also was discussed. As a result, Glass-based fibre optics support growing smart city needs, increasing their use and resulting waste, which should be viewed as a valuable resource, not environmental burden.
Keywords: Recycled glass, Optical Fiber technology, circular economy, smart cities, Sustainable Development Goals (SDGs).

1 INTRODUCTION

The concepts of Circular Economy (CE) and sustainability are becoming more popular in the recent years due to many factors: environmental concerns, ethical issues, global awareness, appearance of new government regulations, economic benefits, technological advancement, and long-term viability. However, these two concepts are different, sustainability is a wider concept that aims to balance between meeting the needs of the present and the ability of future generations to meet their own needs. It merges environmental, economic, and social dimensions, aiming for a balanced approach to development. On the other hand, circular economy is the economic model that focuses on minimizing the waste by recycling the materials and moving from the traditional liner manufacturing: make-use-scrap, to the circular closed loop of product lifecycles through recycling, reusing, and reducing waste. the awareness about the environment and sustainability has accelerated during the last few years. Due to this awareness, the United Nations adopted the seventeen Sustainable goals (17 SDGs) in 2015 as a universal call. The 17 Sustainable Development Goals (SDGs) represent a universal call to action to tackle the world's most urgent social, economic, and environmental challenges by 2030. With clearly defined targets, data-driven frameworks, and broad international support, the SDGs provide a comprehensive roadmap for collaboration among governments, industries, and communities. Their successful implementation is vital to achieving long-term prosperity, resilience, and sustainability for both people and the planet [1]. All countries are tried the last 9 nine years and will try to move faster in the coming six years to achieve the seventeen SDGs and the 169 targets of these goals. One of the approaches that support the achievement of the SDGs is the implementation of Circular economy instead of linear economy.

The "circular economy" is becoming more popular as a strategy for environmental sustainability. Circular systems use sharing, reusing, refurbishing, repairing, recycling, reducing resource inputs, and lessening pollution, waste, and carbon emission to create a closed-loop system. Lieder and Rashid [2] argued that companies must be conduct and

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follow more and more of these rules for being to be aware of those to make a successful transition toward the circular economy. To make such a conversion, companies must develop and reevaluate their currently adopted business models and how they offer value to their customers while also considering ethical and environmental considerations. However, the firms faced many obstacles in the implementation of sustainable plans for a long time [3]. Major barriers during the implementation of the CE were identified were lack of awareness and understanding of CE concepts, limited resources, and the complexity of CE practices [4].

Ortiz-de-Montellano et al. [5] investigate the opportunity of utilizing the circular economy in supporting the advancement of the (SDGs). Their results shows that CE strategies can help achieve almost all Sustainable Development Goals (SDGs), but they are most effective for SDGs 8, 12, and 13, and least effective for SDGs 4, 5, 10, and 16. Another research paper said that the results show that the (CE) is linked to several Sustainable Development Goals (SDGs), including no poverty (SDG 1), responsible consumption and production (SDG 12), sustainable cities and communities (SDG 11), and promoting inclusive and sustainable industrialization and innovation (SDG 9) [6]. However, achieving the Sustainable Development Goals (SDGs) lays the foundation for building smart cities by promoting inclusive urban planning, clean energy, resilient infrastructure, and digital innovation that collectively enable intelligent, sustainable, and liveable urban environments. This achievement and success implementation and integration between the circular economy and smart cities need more than one factors such as advanced sustainable materials, adoption of digital technologies like IoT and AI, and product design optimized for reuse and recyclability. In this research, the focus will be on one technology: glass Fiber optics recycling: challenges and opportunities.

2 FIBER OPTICAL AND SMART CITIES

The main idea of this research to highlight the need to shift the concept of waste from being a challenge to recognizing it as a valuable resource that can be transferred to a money and can be utilized again. The manufacturers, engineers, businessmen, the normal customer or in other words, all stakeholders in all disciplines, need to believe in this view to support the development and achievement of the SDGs and maintain the resources and reduce the environment effects, As shown in figure 1, the consequences of remaining in the traditional economic or in other words, the linear economy.

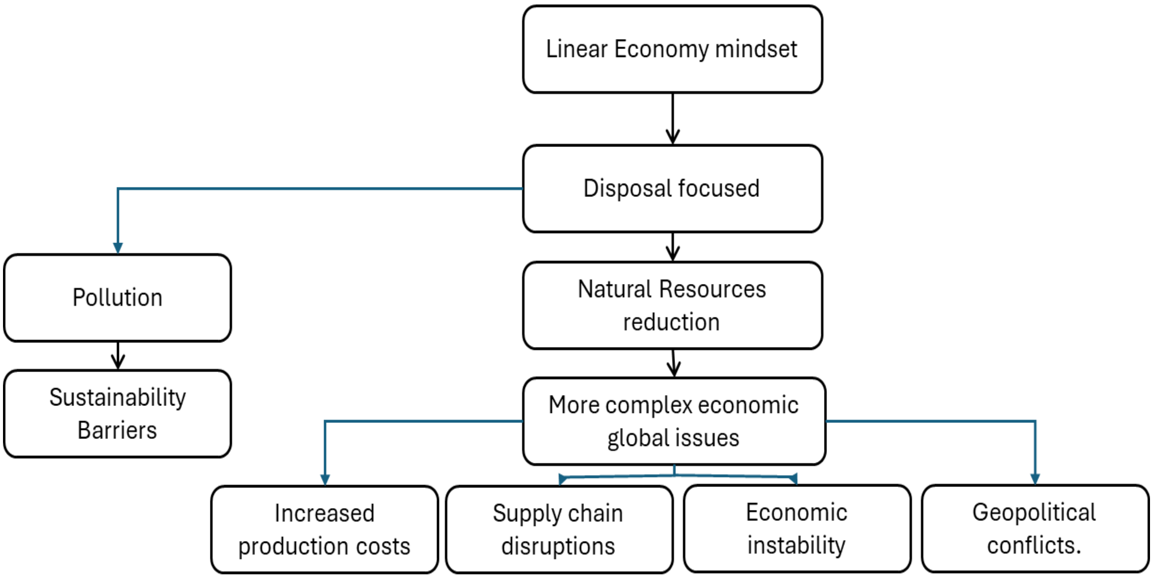

Figure 1. Traditional view of waste as a challenge

Tamminen and Lobin [7] said that in their research that cities must treat waste not as a burden or cost, but as an opportunity for resource recovery. Through analysis of various case studies, they noted continuous advancements in solid waste conversion technologies aimed at enhancing efficiency and sustainability. Among the recycled materials gaining prominence across multiple industries is glass, which holds significant potential for smart city development. A notable innovation is glass fibre optics, which has emerged as a key enabler of smart infrastructure due to its wide range of applications and transformative capabilities. However, the new innovative way to go transfer to the circular economy can lead to different outputs as an advantage such as efficient resource use, clean technology, and resilience urban infrastructure as shown in Figure 2.

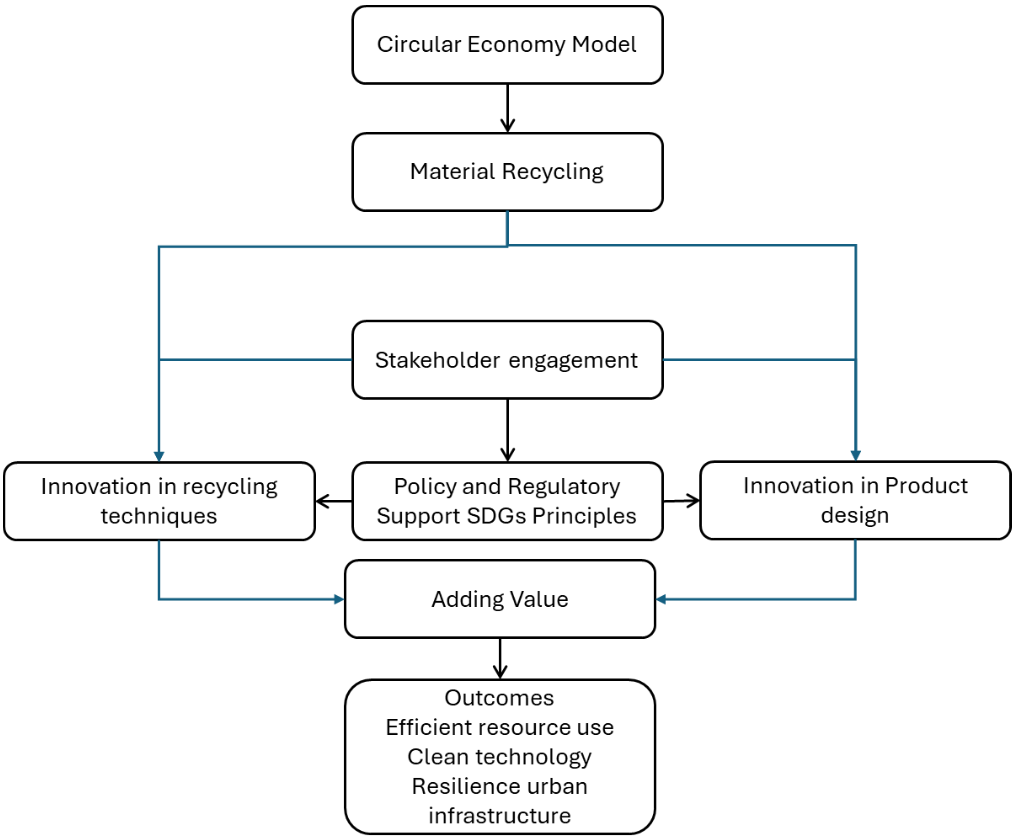

Figure 2: New view of waste as a resource

The figure show that the contribution of all stakeholders to support developing the policies, and to be part of the management of developing the new design of different products and as well as a part of recycling procedures
Glass recycling offers a significant sustainability potential due to its ability to be recycled without quality loss with consistent quality and minimizing challenges in the glass recycling process [8]. Many researchers tried to investigate the opportunity of utilizing and beneficial from the recycled glasses and tried to identify the technological challenges and barriers. However, there are many challenges in remanufacturing the recycled glasses that have been discussed recently in the literatures by different researchers from the point of view of circularity and sustainability as a cornerstone of the smart cities concept.

Yao et al. [9] claims that there is a significant rise and increasing in waste glass generation in recent years, but the advantage is this waste can be recycled efficiently with minimal quality loss, making it a valuable resource for conserving raw materials and energy, and supporting sustainable development due to their stability during recycling process. Recycled glass not only reduces dependence on virgin material but also can maintain all the critical properties-transparency, durability, and thermal stability-which are important in high-performance optical Fibers [10].

Gonçalves et al. [11] made a review of the current status and future prospects of reinforced glass fibre waste management, highlighting the importance of rethinking end-of-life strategies within the waste hierarchy. As waste volumes are expected to rise, the study highlights the pressing need for more efficient collection systems. It reviews various recycling methods, detailing their advantages, drawbacks, and the mechanical properties of the resulting recycled fibres. Although mechanical shredding remains the most widely used method, thermal recycling offers potential due to its ability to retain fibre quality. However, insufficient data on energy consumption limits accurate evaluation of the economic and environmental feasibility of these processes. Despite these challenges, several successful cases demonstrate the potential of integrating recycled glass fibres into new materials with improved mechanical performance. The study concludes with forward-looking recommendations to enhance recycling technologies and support the market integration of recycled glass fibre products.

Bristogianni and Oikonomopoulou [12] explained that although container glass was recycled successfully in Europe, most other types of glass waste are still not. This is mainly because there isn't enough infrastructure to properly collect and separate different kinds of glass, producers are worried about mixing recycled glass that could harm their furnaces, and some products like thin glass lose quality when recycled materials are used. Solving these issues is important to make glass recycling more sustainable and circular. Another researcher, Bulińska et al. [13], investigated the methods for recycling the wind turbine blades at the end of their service life, focusing on recycling glass and glass fibres as valuable secondary raw materials. Their study showed that the major challenges for effective recycling, including technological limitations, regulatory gaps, and economic constraints. Baek et al. [14] highlighted that although glass provides notable environmental advantages due to its recyclability and long lifespan, several obstacles limit its effective use as a sustainable material. Key issues include its heavy weight, fragility, and the high energy demands of production. Moreover, unequal collection systems, slow adoption of recycling technologies, and regulatory shortcomings further considered as a barrier for large-scale recycling.

Carr and Kim [15] discussed the glass recycling from the aspect of environmental economics and supply chain management. They focus on the logistical challenges such as logistical inefficiencies, fluctuating market conditions, and internal organizational factors continue to limit its effectiveness. However, the study also identifies promising opportunities to improve system performance. By tackling these interconnected barriers, stakeholders can enhance recycling efficiency, reduce reliance on landfilling, and advance the sustainability of the glass CLSC.

Souviron and Khan [16] explored the barriers and opportunities for enhancing the recycling and repair of insulating glass units using three methods: a literature review, interviews, and a case study of a glazed office district in Brussels. Their study offers a thorough analysis of the key challenges in managing glass waste within the building sector and emphasizes the critical role of economic instruments in promoting sorting and recycling practices. Additionally, the research highlights the need to redesign insulating glass unit assembly systems to make component separation easier—an important and promising direction for improving recyclability in the construction industry.

Many researchers have been investigated the different applications of the recycled glass and the opportunity in utilizing these advanced materials in a very wide range of application. In the coming section, the different selected application has been presented.

3 APPLICATION OF RECYCLED GLASS

The recycled glass can be utilized in different applications that contributed to the concept of smart cities and sustainability. Kim et al. [17] demonstrate that porous glass derived from recycled waste glass holds significant promise for sustainable manufacturing and environmental remediation. Its tunable porosity, chemical inertness, and high sorption capacity make it an efficient material for pollutant removal and other industrial applications. The study highlighted the possibility of integrating recycled materials into high-value products, aligning with circular economy principles and contributing to environmental protection through innovative material design.

Paul et al. [18] said that utilizing recycled waste glass in concrete can be useful in achieving sustainable construction by reducing the demand for natural raw materials and minimizing the environmental impact of glass waste. They claim that, while recycled glass can improve the mechanical strength and durability of concrete, its performance is influenced by key factors such as particle size, replacement proportion, and long-term behaviour. The authors stressed the need for further research to optimize mix designs, control the alkali-silica reaction, and develop standardized practices for broader adoption. Advancing this solution could significantly contribute to glass waste reduction and lower CO_2 emissions in the construction industry.

Nodehi and Mohamad [19] investigated the possibility of integrating and utilizing the recycled glass into the construction sector. Their study highlights that partially replacing cement or aggregates with recycled glass can lead to an average reduction of 19% in greenhouse gas emissions and 17% in energy consumption, and notable cost savings. Technically, the use of waste glass in concrete improves fresh properties, enhances fire resistance, lowers permeability, and, when finely ground, exhibits favourable cementitious behaviour. These benefits position recycled glass as a valuable and sustainable alternative in modern construction practices.

Ting et al. [20] explained that using recycled glass in 3D concrete printing is a promising way to reduce glass waste and support sustainable building. They noted that, unlike regular recycling, 3D printing can use unsorted recycled glass as fine aggregate, removing the need for colour sorting. Although this type of concrete has lower strength than sand-based mixes, it flows better, which is useful for 3D printing. The authors suggested more research is needed to improve the mix by combining sand and recycled glass, adjusting particle size, and adding materials to boost strength and printability.

Another researcher, focus on the barriers the need for better recycling methods that preserve fibre strength [21]. They found that thermal recycling is significantly weakens the tensile strength of E-glass fibres, mainly depending on how hot and how long the heating lasts. They noted that the type of furnace atmosphere affects strength only at low temperatures or short heating times but has little impact at higher temperatures. Their analysis showed that surface damage worsened by heat and moisture is the main reason for the strength loss. Importantly, this damage is not recovered when making new composites, resulting in weaker final products.

Delbari and Hof [22] highlight the challenges in conventional glass waste management and the inherent complexities of recycling processes. Their study discussed the critical role of recycling in saving the resources and supporting circular economy objectives. The authors explore emerging techniques for recovering high-value materials, such as chemically strengthened glass, and identify key research gaps that hinder the effective recovery of high-quality glass products. Furthermore, their research paper covers the transformative potential of Industry 4.0 and 5.0 technologies in enhancing glass recovery practices through smart systems, real-time data, and intelligent automation.

Ahmed and Rana [23] discussed the critical properties of recycled glass concrete from the aspect of workability, air content, and microstructure. They evaluate the mechanical performance of recycled glass concrete when recycled waste glass is used as a partial substitute for sand, cement, or coarse aggregates. Their results show that up to 20% replacement of sand can improve the strength.

None of the innovative applications for recycled glass was presented in a study that introduced a novel technology for converting glass waste into building components. The material underwent rigorous performance assessments and was successfully validated for use in drainage pit lids. The results demonstrated that the technology is both sustainable and adaptable for broader use across various engineering applications [24]. However, many researchers presented the advantages and limitations of utilizing the fibre optical that aligned with sustainable applications such as Glass Fiber Reinforced Concrete (GFRC) which incorporates glass fibres, has been shown to offer substantial advantages over traditional concrete in Smart City applications. It delivers superior mechanical performance, including increased strength, durability, and resistance to environmental stressors, leading to extended service life and lower maintenance requirements. While the initial cost is higher, GFRC enhances thermal insulation and can reduce CO_2 emissions by up to 17%, aligning with sustainability goals. Additionally, its design flexibility supports the development of innovative, user-focused urban environments [25]. Ismaila, [26] tried to investigate the role of Fiberglass Reinforced Concrete (FRC) in uniting architectural creativity with civil engineering demands. The study identifies FRC as a structurally robust, cost-effective, and environmentally resilient material that enhances long-term building performance. Its adaptability allows for the realization of intricate architectural forms beyond the limitations of traditional materials.

Zhang et al. [27] said that understanding the strain transfer mechanism is critical for the accurate interpretation of strain data from Fiber optic sensors. They said that despite its importance, experimental research on strain transfer particularly for Fiber optic cables embedded in cementitious materials remains limited. Their study addresses this gap by investigating the strain transfer behaviour of optical Fiber cables embedded in concrete cubes under boundary conditions that induce displacement discontinuities. They compare the performance of different cable types under increasing strain levels and examines the nonlinear behaviour of force–displacement relationships and strain distributions during cyclic loading. Mechanical properties of the cables are also assessed, and a new parameter is introduced to quantify the strain transfer length. Their findings offer practical insights to guide researchers and engineers in selecting appropriate Fiber optic cables for strain sensing and in accurately interpreting sensor data for structural health monitoring systems.

Ballato and Dragic [28] highlighted the pivotal role of optical fibre-based lasers and amplifiers in a wide array of applications, including telecommunications, metrology, sensing, manufacturing, machining, and directed energy systems. Although these technologies are highly efficient, even small amounts of heat generated from a minor fraction of the optical power can adversely affect system performance. Their study revisits the enabling role of glass in achieving fully passive thermal management for active fibre systems. By integrating educational insights with recent advancements, the authors examine how specific glass compositions can reduce heat generated by active dopants and how properties such as thermo-optic and thermal expansion coefficients can be optimized to counteract thermal distortions. Their findings emphasize the critical role of advanced glass engineering in improving the efficiency and stability of high-performance optical Fiber technologies.

Saccani et al. [29] investigated the glass produced by combining recycled glass with silicate waste focusing on its electrical performance across varying temperatures and frequencies. Their study showed that increasing the proportion of incinerator waste, which results in lower alkali and higher alkaline-earth content, led to decreased electrical conductivity and dielectric losses. These changes made the glass resemble the properties of type E glass fibres, indicating its potential suitability for high-voltage insulator applications. Siad et al. [30] conducted a study aimed at enhancing the strength and sustainability of high-volume fly ash engineered cementitious composites (HVFA-ECC) by incorporating recycled glass powder (RGP). The experimental results confirmed that adding RGP significantly improved compressive and flexural strengths, chloride ion resistance, and electrical resistivity, while maintaining ductility comparable to standard ECC with a fly ash-to-cement ratio of 1.2. Additionally, the inclusion of RGP accelerated the self-healing capability of HVFA-ECC and improved the final recovery of both strength and physical properties.

Recycled glass can present optical performance equal to that of virgin silica due to its amorphous nature. Its transparency ensures that no light is scattered or absorbed; in other words, signal integrity remains unaffected even at much longer distances because small losses have great adverse impacts on communication efficiency [31]. Recycled glass plays an important role in promoting sustainability within the fibre optics industry, as both share silica as a primary material. While optical fibres require ultra-high purity silica, advancements in purification and pre-treatment technologies have opened possibilities for incorporating recycled glass into the production process. Using recycled glass not only reduces reliance on virgin raw materials but also lowers energy consumption and greenhouse gas emissions, aligning with global efforts to achieve Sustainable Development Goals such as responsible consumption and climate action. Integrating recycled glass into fibre optic manufacturing supports the circular economy by minimizing waste, conserving resources, and contributing to more environmentally responsible production practices.

4 IMPACTS ON SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The increasing demand for Optical Fibers in different applications such as high-speed communication, high speed internet, smart application in different infrastructure component, traffic management systems, healthcare systems and data and information security brought increased attention to their environmental impact. At the same time, rising awareness of the importance of achieving the United Nations Sustainable Development Goals (SDGs), particularly those related to sustainable industry, responsible consumption, and climate action (SDGs 9, 12, and 13), has underscored the urgent need to rethink the life cycle of optical fibre products. This convergence of technological advancement and sustainability imperatives highlights the necessity for intensified research into integrating circular economy principles within the manufacturing and recycling processes of optical fibres. Such efforts would focus on reducing raw material extraction, minimizing production waste, enhancing reuse and recycling of glass and polymer components, and developing energy-efficient processing methods. Advancing circular strategies in the optical fibre industry is essential not only to reduce its environmental footprint but also to align with long-term global sustainability goals.

4.1 High-Speed Internet

Optical fibres serve as one of most important components in high-speed broadband and 5G networks, enabling fast and reliable connectivity across smart cities therefore this technology play a key role in modern communication by enabling fast, reliable, and high-capacity data transmission. They support a wide range of services, including residential internet, business networks, and mobile communications. A typical optical network consists of three layers: core, metro, and access networks, which together form an end-to-end communication system (Liu, X. (2019)[32]. Another researcher Zheng [33] claim that optical fibres is a core components of global communication infrastructure, are capable of transmitting data over long distances with minimal loss through principles like total internal reflection.

Kaur et al. [34] said that the optical fiber communication as significant use of laser technology, are important technology for the information era. They claim that with the rise of the Internet of Things (IoT), big data, cloud computing, virtual reality, and artificial intelligence, will increasing the demand for the development and performance standards of optical fibre communication. This aligns directly with the SDG 11 Sustainable Cities and Communities because 5G enables smart city infrastructure, including smart transportation, energy systems, and public services. and SDG 9 Industry, Innovation and Infrastructure, especially Target 9.c: "Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries.

4.2 Traffic Management Systems

The rapid transformation of smart city infrastructure has clearly increased the need for expanded optical fibre networks to support fast and efficient communication—especially for systems like traffic control, surveillance, and IoT devices [35]. One research conducted by [36] Pham et al., proposed a vehicle-to-pedestrian (V2P) communication system that highlights the crucial role of optical fibres in enhancing urban traffic safety. In their design, light-transmitting concrete (LTC) panels embedded with PMMA optical fibres of various core diameters are used to transmit traffic signals. These optical fibres enable the panels to display clear visual warnings and receive signals from pedestrians and vehicles. By investigating the optical performance of these fibres within the LTC structure, the study demonstrates how optical fibre integration can significantly improve communication efficiency and safety in smart city environments. This contribution and role are linked directly to the SDG 11: Sustainable Cities and Communities, Target 11.2: "By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all"

Litzenberger et al., [37] claim that the use of Fiber optic acoustic sensing (FOAS) offers a breakthrough in real-time traffic monitoring by using existing telecom fibre networks to capture vehicle movement over long distances. Unlike traditional sensors limited to fixed points, FOAS enables continuous, seamless traffic data collection, improving accuracy and reducing costs. This innovation enhances urban mobility and supports sustainable infrastructure, aligning with SDG 9 and SDG 11 goals for smarter, more efficient cities.

4.3 Surveillance and Security Systems

Surveillance and security systems in smart cities play a significant role in achieving the Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 16 (Peace, Justice and Strong Institutions). By leveraging advanced technologies such as fibre optic networks for real-time monitoring, these systems enhance public safety, support crime prevention, and ensure rapid emergency response thereby fostering safer, more resilient, and inclusive urban environments.

Zhang [38] developed a boundary security alarm system based on fibre optic sensing and optical communication technologies. The system integrates fibre optic sensors, linkage devices, signal processors, and switches to deliver accurate intrusion detection with low false alarm rates. It is highly adaptable to various environments and supports flexible, independent monitoring of multiple zones. Compared to conventional systems, it enhances reliability, stability, and cost-effectiveness, thereby significantly strengthening perimeter security.

4.4 Healthcare and Emergency Services

In smart cities, optical fibre can be the foundation for better healthcare and emergency services, this contribution aligned directly with SDG 3 and SDG 11. Fast and reliable fibre optic communication allows doctors to provide care remotely (telemedicine), monitor patients in real time, and quickly share important health information with emergency teams. This infrastructure ensures seamless, resilient service delivery, improving urban health outcomes and emergency preparedness.

Leal-Junior et al. [39] emphasized that optical fibres—particularly polymer optical fibres (POFs)—are emerging as transformative tools in healthcare due to their distinctive physical characteristics and versatility. These include electromagnetic immunity, high flexibility, low Young's modulus, and strong impact resistance, which together support their integration into precise and patient-friendly medical systems. The review highlights the widespread application of POF-based sensors in monitoring physiological parameters, analysing human movement, and enhancing wearable medical devices such as exoskeletons and smart prosthetics. These findings point to a growing role for optical fibre technology in advancing future healthcare instrumentation. Leal-Junior et al. [40] highlight the strong potential of optical fibre sensor systems in transforming wearable healthcare technologies. These sensors meet new demands arising from the integration of the Internet of Things, photonics advancements, and AI algorithms, offering effective solutions for monitoring musculoskeletal disorders and other health issues. With uses in smart textiles, biosensors, and self-powered systems, optical fibre technologies provide a reliable and forward-looking alternative to conventional sensors, enabling the next generation of wearable health devices.

4.5 Smart Buildings and Infrastructure Monitoring

Fiber optic technology offers a highly effective and reliable solution for monitoring the durability of concrete structures, especially in harsh and demanding environments. With their high sensitivity, resilience, and ability to be embedded within the material, fibre optic sensors enable real-time tracking of critical factors such as pH, ion penetration, carbonation, and corrosion. Their application supports the development of smart, self-monitoring concrete systems, paving the way for more resilient, sustainable, and long-lasting infrastructure [41].

Su et al. [42] stated that optical fibre-based translucent concrete (OFTC) offers a novel solution for enhancing building energy efficiency by embedding optical fibres into concrete to transmit daylight. Their study underscores the key role of optical fibres in improving natural lighting and reducing electricity usage, especially when OFTC walls are used alongside windows. They found that design variables—such as the volume of fibres, their numerical aperture, glazing type, and window-to-wall ratio—significantly affect performance. Buildings incorporating OFTC with high numerical aperture fibres achieved up to 32.07% lower electricity use compared to conventional wall systems. While increased light transmission may slightly raise the risk of glare, its impact remains limited in buildings with larger window areas. Overall, Su et al. concluded that optical fibres are essential to OFTC's performance, enabling smart, light-transmitting building materials that support both energy savings and visual comfort. So, it directly contributes to the SDG 9 and SDG 11

5 CONCLUSIONS

This research underscores the transformative potential of recycled glass in advancing optical fibre technology for sustainable smart cities. Through a comprehensive exploration of its chemical, mechanical, and optical properties, the study demonstrates the viability of recycled glass as a sustainable alternative to virgin silica. Key innovations, such as nano-reinforcement and advanced coating technologies, highlight solutions to challenges like material fatigue and brittleness, ensuring durability and high performance in extreme conditions.

Optical fibre technologies contribute significantly to achieving multiple Sustainable Development Goals (SDGs). They enhance SDG 3 by enabling telemedicine, wearable health monitoring, and efficient emergency services. In support of SDG 9, fibre optics drive innovation in communication infrastructure, powering 5G, IoT, and smart industry applications. For SDG 11, they enable sustainable urban systems, including smart traffic control, energy-efficient buildings, and resilient infrastructure. Additionally, fibre-based surveillance systems align with SDG 16, strengthening public safety and institutional security through real-time monitoring and reliable intrusion detection. Collectively, these technologies are essential for building inclusive, innovative, and sustainable smart cities of the future. In conclusion, fibre optics made from glass are increasingly used across many industries, especially with the growing demand for smart cities and environmental solutions. As their applications continue to expand, more glass fibre waste will be generated—making it essential to treat this waste as a valuable resource, not just as garbage.

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