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Crack Closure in Cementitious Infrastructure Elements under Self Healing Materials and Damage Accumulation

Jonathan Chu*, Nicole Chau

Department of Civil Engineering, Faculty of Engineering, University of Hong Kong, Hong Kong, Hong Kong SAR, China

Corresponding author: jonathan.chu@hku.hk

Abstract

The degradation of cementitious infrastructure elements presents a monumental challenge to global civil engineering, necessitating continuous maintenance and immense financial expenditure. Central to this degradation is the accumulation of damage over time, which manifests primarily as microcracking under the influence of structural loads and environmental stressors. This paper investigates the intricate mechanisms of damage accumulation and the subsequent processes of crack closure facilitated by self-healing materials. By integrating both autogenous and autonomous self-healing paradigms, the study elucidates how intrinsic chemical reactions and engineered biological or polymeric interventions mitigate crack propagation. The analysis encompasses the microstructural degradation pathways that initiate failure, followed by a comprehensive review of the methodologies utilized to evaluate self-healing efficacy, including non-destructive imaging and mechanical recovery testing. Results synthesize current data on crack closure ratios, demonstrating that while autogenous healing is limited to narrow crack widths, autonomous mechanisms, particularly those utilizing encapsulated bacterial agents, offer substantial improvements in closing wider fissures and restoring structural integrity. Ultimately, this research provides a holistic understanding of the interplay between damage progression and autonomic repair, highlighting pathways for transitioning these advanced smart materials from laboratory settings to full-scale infrastructural applications, thereby significantly extending the service life of concrete structures.

Keywords: Self-Healing Concrete; Damage Accumulation; Crack Closure; Cementitious Materials; Self Healing Materials

1. Introduction

1.1 The Context of Infrastructure Aging and Degradation

Modern society relies heavily on robust infrastructure systems, the vast majority of which are constructed using concrete due to its exceptional compressive strength, versatility, and cost-effectiveness. However, cementitious materials are inherently brittle and possess relatively low tensile strength, rendering them highly susceptible to cracking. Over their service life, structural elements such as bridges, dams, and highway pavements are continuously subjected to a myriad of degrading forces. These forces include fluctuating mechanical loads, thermal variations, freeze-thaw cycles, and aggressive environmental chemical attacks. The initial stages of degradation often manifest as microscopic fissures within the cement matrix. While these microcracks may not immediately compromise the load-bearing capacity of the structure, they create critical pathways for the ingress of deleterious substances such as water, chloride ions, sulfates, and carbon dioxide.

The penetration of these substances initiates secondary deterioration mechanisms, most notably the corrosion of embedded steel reinforcement. As the reinforcing steel corrodes, the formation of expansive rust products generates internal tensile stresses that further widen existing cracks, leading to a vicious cycle of accelerated damage accumulation [1]. The global economic implications of this degradation are staggering.

Annual expenditures for the maintenance, repair, and rehabilitation of deteriorating concrete infrastructure consume a significant portion of national civil engineering budgets worldwide [2]. In many developing and developed nations alike, the backlog of required structural maintenance vastly exceeds available funding, prompting a critical need for innovative materials that can inherently resist degradation and reduce the frequency of manual interventions [3]. The traditional approach to structural design largely accepts cracking as an unavoidable reality, attempting to control crack widths through reinforcement detailing rather than preventing them entirely. However, the shift toward sustainable and resilient engineering necessitates a fundamental change in how damage is managed, moving away from passive acceptance toward active, autonomous mitigation [4].

1.2 The Paradigm of Self-Healing Concrete

In response to the pervasive issue of crack formation and subsequent damage accumulation, the concept of self-healing cementitious materials has emerged as one of the most promising advancements in materials science. Drawing inspiration from biological systems, such as the regeneration of human skin or the mending of fractured bones, self-healing concrete is designed to autonomously detect and repair internal damage without the need for external human intervention [5]. The primary objective of this technology is to achieve complete crack closure, thereby restoring the material to its original state of impermeability and preventing the ingress of aggressive agents.

Self-healing mechanisms in concrete are broadly categorized into two main types: autogenous healing and autonomous healing. Autogenous healing refers to the natural, intrinsic ability of traditional cementitious mixtures to heal small cracks. This process is predominantly driven by two distinct chemical reactions. First, the ongoing hydration of unreacted cement particles exposed to moisture when a crack forms. Second, the carbonation of calcium hydroxide, a byproduct of initial cement hydration, which reacts with carbon dioxide dissolved in penetrating water to precipitate calcium carbonate. While beneficial, autogenous healing is generally restricted to very fine cracks, typically those less than a fraction of a millimeter in width, and requires the continuous presence of water to facilitate the chemical reactions [6].

To overcome the limitations of autogenous processes, researchers have developed autonomous self-healing materials. These engineered systems involve the deliberate incorporation of unconventional healing agents into the concrete matrix during the mixing phase. Common autonomous approaches include the use of microcapsules filled with polymeric adhesives, vascular networks containing liquid healing compounds, and bio-mineralizing bacteria embedded with specific nutrient sources [7]. When a crack propagates through the matrix, it ruptures the capsules or activates the dormant biological agents, releasing the healing compounds directly into the fissure. The subsequent chemical or biological reactions physically seal the crack, demonstrating a capacity to heal significantly wider damage compared to autogenous methods [8]. The integration of these smart materials represents a paradigm shift from traditional, static infrastructure to dynamic, responsive structural elements capable of self-preservation.

2. Literature Review and Theoretical Background

2.1 Evolution of Self-Healing Concepts in Materials Science

The conceptualization of self-healing materials originated in the broader field of polymer science before being adapted for civil engineering applications. Early theoretical models proposed that structural materials could be imbued with localized repair mechanisms triggered by the specific energy release associated with crack propagation. In the context of cementitious composites, the historical recognition of autogenous healing dates back over a century, with engineers noting that hairline cracks in retaining walls and aqueducts would occasionally seal themselves over time when exposed to stagnant water [9]. However, it was not until the late twentieth century that systematic academic investigations began to quantify the exact physical and chemical parameters governing this phenomenon.

The transition from observing natural autogenous healing to engineering autonomous repair mechanisms marks a significant leap in the literature. Initial experiments in autonomous concrete healing heavily relied on encapsulation technologies adapted from the pharmaceutical industry. Researchers synthesized fragile microcapsules containing cyanoacrylates or epoxy resins and embedded them into mortar specimens.

Mechanical testing revealed that propagating microcracks would effectively cleave these capsules, releasing the resin to polymerize and bond the crack faces together [10]. While successful in controlled laboratory environments, these early polymeric systems faced challenges regarding the long-term survivability of the capsules during the aggressive concrete mixing process and the potential alteration of the concrete bulk mechanical properties.

Table 1: Comparison of Self-Healing Mechanisms in Cementitious Materials

Mechanism Type	Primary Agents	Trigger Condition	Maximum Crack Width
Autogenous	Unhydrated cement, calcium carbonate	Water ingress	0.1 to 0.3 millimeters
Autonomous Bacterial	Bacillus spores, nutrient broth	Water and oxygen	0.5 to 0.8 millimeters
Autonomous Encapsulation	Polyurethane, epoxy resins	Mechanical rupture	0.8 to 1.0 millimeters

2.2 Autogenous versus Autonomous Healing Modalities

The academic discourse heavily contrasts the reliability, scalability, and economic viability of autogenous versus autonomous modalities. Enhancing autogenous healing has been a major focus for researchers aiming for cost-effective solutions. Strategies to amplify this intrinsic property include restricting the initial water-to-cement ratio to ensure a vast reserve of unhydrated cement clinker remains in the hardened matrix. Additionally, the incorporation of highly reactive supplementary cementitious materials, such as blast furnace slag or pulverized fly ash, has been shown to prolong the latent hydration potential of the matrix [11]. Superabsorbent polymers have also been utilized to facilitate autogenous repair; these polymers absorb large quantities of water during wet periods and slowly release it to internal unhydrated particles during dry spells, maintaining the moisture required for continuous chemical precipitation [12].

Conversely, the literature on autonomous healing is rapidly expanding, with bio-mineralization emerging as a particularly innovative frontier. The biological approach typically employs alkali-resistant, endospore-forming bacteria, such as species from the Bacillus genus. These spores can remain dormant within the highly alkaline concrete environment for decades. Upon the formation of a crack and the subsequent ingress of atmospheric moisture and oxygen, the spores germinate. Utilizing embedded organic precursors like calcium lactate, the active bacteria undergo metabolic processes that result in the copious precipitation of extracellular calcium carbonate crystals [13]. This microbiologically induced calcite precipitation has demonstrated remarkable efficacy in completely bridging cracks, thereby restoring the water-tightness of the structural element. While biological methods offer superior crack closure capacities, the literature notes ongoing challenges regarding the cost of cultivation, the equitable distribution of spores within large concrete volumes, and the necessity of protecting the biological agents from the sheer forces of mixing through protective encapsulation in materials like expanded clay particles or extruded geopolymers [14].

3. Mechanisms of Damage Accumulation in Cementitious Elements

3.1 Microstructural Degradation Pathways

To fully comprehend the efficacy of crack closure technologies, one must rigorously examine the mechanisms through which damage accumulates within the cementitious infrastructure. Concrete is a highly heterogeneous composite material consisting of coarse aggregates, fine aggregates, unhydrated cement particles, and a porous hydrated cement paste matrix. The transition zone between the aggregate surface and the cement paste, often referred to as the interfacial transition zone, is characteristically the weakest link in this composite structure due to higher porosity and local microstructural variations [15]. Under applied stresses, strain incompatibilities between the rigid aggregates and the relatively softer paste lead to stress concentrations precisely at this interfacial zone.

Damage accumulation typically initiates at the microscopic scale. When the localized tensile stresses exceed the tensile strength of the interfacial transition zone, debonding occurs, resulting in the formation of isolated microcracks. Initially, these microscopic defects are uniformly distributed and stable, causing no immediate threat to macroscopic structural integrity. However, under sustained or cyclic loading conditions, these individual microcracks begin to propagate and interact. The stress fields surrounding the tips of adjacent microcracks overlap, causing them to coalesce into larger, continuous macroscopic cracks [16]. This progressive linking of defects reduces the effective load-bearing cross-sectional area of the structural element, decreasing its overall stiffness and leading to non-linear macroscopic deformation. The rate of this degradation is highly dependent on the magnitude of the applied loads, the frequency of loading cycles, and the inherent fracture toughness of the specific concrete mixture.

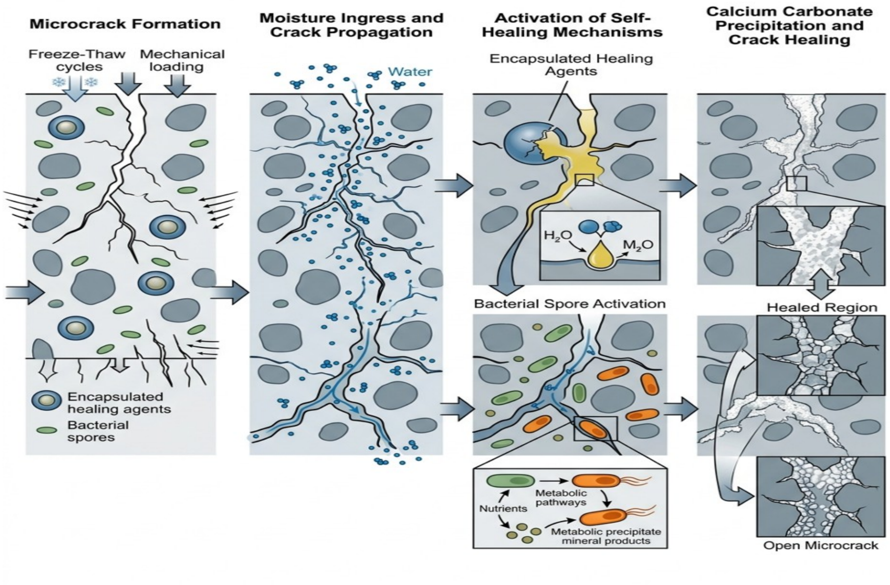

Figure 1: Comprehensive Schematic of Damage Accumulation and Self

3.2 Environmental Stressors and Crack Propagation

While mechanical loading provides the primary driving force for crack initiation, environmental stressors play an equally critical role in the continuous accumulation of damage and the acceleration of crack propagation. Temperature fluctuations induce significant volumetric changes within cementitious elements. In massive concrete structures, the heat generated by the exothermic hydration of cement can cause steep thermal gradients between the interior core and the exterior surface. As the surface cools and contracts while the core remains warm and expanded, severe tensile stresses develop at the surface, often exceeding the early-age tensile strength of the concrete and resulting in extensive thermal cracking [17].

Furthermore, in geographic regions subjected to severe winter climates, freeze-thaw cycling constitutes a major degradation mechanism. Water that has permeated into the capillary pores of the concrete expands in volume by approximately nine percent upon freezing. If the concrete is critically saturated, this volumetric expansion generates immense internal hydraulic and osmotic pressures. When these pressures exceed the tensile capacity of the surrounding cement matrix, extensive internal microcracking ensues [18]. Repeated cycles of freezing and thawing cause cumulative damage, progressively deteriorating the concrete from the outer surface inward. The introduction of self-healing mechanisms into such environments aims to intercept this cycle; by sealing the initial ingress pathways early in the structure's life, the self-healing agents drastically reduce the volume of penetrable water, thereby mitigating the catastrophic internal pressures associated with subsequent freezing events.

4. Methodologies for Evaluating Crack Closure and Self-Healing

4.1 Non-Destructive Testing and Imaging Techniques

The accurate quantification of self-healing efficiency and crack closure relies heavily on advanced analytical methodologies. Because the processes of damage accumulation and subsequent healing occur internal to the opaque concrete matrix, non-destructive testing and high-resolution imaging techniques are indispensable. Acoustic emission testing is widely utilized to monitor both the formation of microcracks and the activation of autonomous healing mechanisms in real-time. When a crack propagates or a microcapsule ruptures, it releases transient elastic waves that propagate through the material. By attaching an array of piezoelectric sensors to the surface of the concrete element, researchers can capture these acoustic signals, pinpointing the precise location, timing, and magnitude of internal damage events [19].

For the visualization of crack closure, X-ray micro-computed tomography has become the gold standard in academic research. This non-destructive imaging technique allows for the three-dimensional reconstruction of the internal concrete microstructure. By scanning a concrete specimen before and after the application of a healing protocol, researchers can visually and quantitatively analyze the volume, morphology, and spatial distribution of the newly precipitated healing products within the crack networks [20]. Furthermore, digital image correlation offers a powerful tool for monitoring surface crack dynamics during mechanical loading. By tracking the displacement of a random speckle pattern applied to the specimen surface, digital image correlation provides high-resolution, full-field strain maps, enabling the precise measurement of crack opening displacements and subsequent closure behaviors during the healing phase [21].

4.2 Mechanical Recovery Assessment

While visual crack closure and the restoration of impermeability are critical, the ultimate measure of structural healing is the recovery of mechanical properties. Assessing mechanical recovery typically involves a two-stage testing protocol. First, concrete specimens are subjected to controlled loading, such as three-point or four-point bending, to induce a predetermined level of damage or a specific crack width. The load is then removed, and the specimens are placed in specific environmental conditions to facilitate the desired self-healing mechanisms [22]. After a designated healing period, which may range from a few days to several months, the specimens are reloaded to failure.

During the reloading phase, several parameters are meticulously evaluated to quantify healing efficiency. The recovery of stiffness is a primary indicator; a successfully healed specimen will demonstrate an initial reloading stiffness that is significantly higher than the unloading stiffness of the damaged state, indicating that the crack faces have been effectively bridged by a rigid material. Additionally, the recovery of load-bearing capacity is measured by comparing the maximum load achieved during the secondary loading phase to the initial cracking load [23]. High-performance autonomous healing systems, particularly those utilizing strong polymeric adhesives, can sometimes restore the load-bearing capacity to levels matching or even slightly exceeding the original uncracked strength. However, for systems relying on calcium carbonate precipitation, such as autogenous and bacterial methods, the mechanical strength recovery is often partial, as the precipitated calcite is significantly weaker in tension than the surrounding cement matrix. In these cases, the primary benefit observed during mechanical testing is the substantial recovery of environmental resistance rather than full tensile structural capacity.

5. Results of Autogenous and Autonomous Healing Efficacy

5.1 Analysis of Crack Closure Ratios

Extensive laboratory investigations and preliminary field trials have yielded a robust dataset regarding the efficacy of various self-healing modalities in achieving complete crack closure. The most commonly reported metric in the literature is the crack closure ratio, defined as the percentage reduction in the surface crack area or width after a specified healing period relative to the initial damaged state. Experimental results consistently demonstrate that autogenous healing, while ubiquitous in standard concrete, is highly constrained by the geometric parameters of the crack. Specifically, purely autogenous mechanisms exhibit high closure ratios for crack widths below one hundred and fifty micrometers [24]. For cracks exceeding this threshold, the natural precipitation of calcium carbonate and secondary hydration products is insufficient to bridge the gap before the active components are depleted or washed away by flowing water.

In stark contrast, autonomous healing systems display vastly superior crack closure capabilities. Bacterial self-healing concretes have consistently demonstrated the ability to completely seal cracks ranging from four hundred to eight hundred micrometers in width, provided adequate moisture and oxygen are available to sustain microbial metabolism [25]. The precipitation of microbiologically induced calcium carbonate is dense and highly crystalline, filling the void space efficiently over a period of three to six weeks. Similarly, encapsulated polymeric systems report nearly instantaneous crack closure upon rupture, effectively sealing cracks up to one millimeter wide. The rapid polymerization of agents like polyurethane physically blocks the crack mouth, preventing immediate fluid ingress and stabilizing the localized damage zone against further environmental degradation [26].

Table 2: Representative Crack Closure Efficacy Across Healing Modalities

Healing Modality	Initial Crack Width	Healing Environment	Closure Ratio Achieved
Standard Autogenous	0.2 millimeters	Continuous water immersion	85 percent
Bacterial Admixture	0.6 millimeters	Wet-dry cycling	92 percent
Polymeric Encapsulation	0.8 millimeters	Ambient atmospheric conditions	98 percent

5.2 Long-Term Durability Enhancements

The overarching goal of implementing self-healing materials in infrastructure is the significant enhancement of long-term durability and the extension of service life. Results evaluating post-healing transport properties confirm that successful crack closure dramatically reduces the permeability of the concrete elements. Permeability tests utilizing pressurized water flow indicate that extensively cracked specimens exhibit flow rates several orders of magnitude higher than uncracked controls. Following successful biological or polymeric healing, the flow rates are routinely reduced to levels nearly indistinguishable from intact concrete [27].

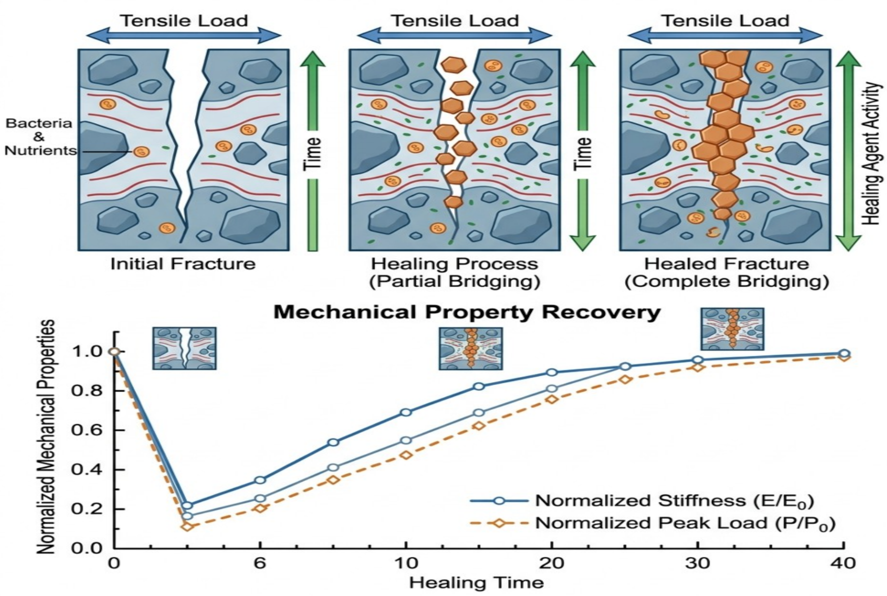

Figure 2: Detailed Cross

This restoration of impermeability directly translates to a robust defense against chloride-induced corrosion. Accelerated chloride migration tests conducted on healed specimens show a massive reduction in the depth of chloride penetration compared to their unhealed counterparts. By preventing chlorides from reaching the critical depth of the steel reinforcement, self-healing technologies fundamentally arrest the primary cause of premature structural failure in marine and highway bridge environments. Consequently, predictive lifecycle modeling based on these experimental results suggests that the integration of self-healing mechanisms could extend the maintenance-free service life of critical infrastructure elements by several decades, thereby validating the initial higher material costs associated with biological agents or specialized microcapsules [28]. The long-term durability results firmly establish self-healing technology not merely as a novel material property, but as a mandatory evolutionary step for sustainable civil infrastructure.

6. Conclusion and Future Perspectives

6.1 Synthesis of Findings

The comprehensive investigation into damage accumulation and self-healing mechanisms within cementitious infrastructure elements highlights a transformative shift in structural materials science. As detailed throughout this paper, the deterioration of concrete structures is an inevitable consequence of microstructural degradation pathways initiated by mechanical loads and exacerbated by environmental stressors such as thermal gradients and freeze-thaw cycles. Left unchecked, the coalescence of these microscopic defects into macroscopic fissures compromises structural integrity and drastically shortens service life. However, the application of self-healing technologies provides a robust and autonomous defense mechanism. While intrinsic autogenous healing offers localized repair for minor damage through delayed hydration and carbonation, engineered autonomous systems utilizing encapsulated polymers or dormant bacterial spores demonstrate a profound capacity to seal significantly wider cracks. The integration of high-resolution imaging and mechanical testing verifies that these mechanisms not only restore the physical continuity of the cement matrix but fundamentally recover the material's impermeability, thereby halting secondary degradation processes like reinforcement corrosion.

6.2 Future Implementations and Standardization

Despite the overwhelmingly positive results observed in controlled laboratory environments, the transition of self-healing concrete into ubiquitous commercial application requires addressing several outstanding challenges. Future research must prioritize the optimization of healing agents to ensure long-term survivability over the extended lifespans typical of civil infrastructure. Furthermore, the economic scalability of producing biological spores or specialized microcapsules on an industrial scale remains a critical hurdle. To facilitate widespread adoption, the global civil engineering community must develop standardized testing protocols and specialized building codes that explicitly account for the dynamic properties of self-healing materials. As predictive modeling and field demonstrations continue to mature, the eventual standardization of these smart cementitious composites promises to drastically reduce the economic and environmental burdens of infrastructure maintenance, paving the way for a new era of highly resilient and self-sustaining urban environments.

References

1. World Economic Forum (WEF). Global Risks Report; World Economic Forum: Cologny, Switzerland, 2025; Available online: https://www.weforum.org/publications/global-risks-report-2025/ (accessed on 5 November 2025).

2. The Economist Intelligence Unit (EIU). An Eco-Wakening: Measuring Global Awareness, Engagement, and Action for Nature; The Economist Intelligence Unit: London, UK, 2021; Available online: https://impact.economist.com/sustainability/ecosystems-resources/an-eco-wakening-measuring-global-awareness-engagement-and-action-for-nature (accessed on 5 November 2025).

3. Chausson, A.; Welden, E.A.; Melanidis, M.S.; Gray, E.; Hirons, M.; Seddon, N. Going beyond market-based mechanisms to finance nature-based solutions and foster sustainable futures. PLoS Clim. 2023, 2, e0000169.

4. Barbier, E.B. The Water Paradox: Overcoming the Global Crisis in Water Management; Yale University Press: New Haven, CT, USA; London, UK, 2019; Available online: https://yalebooks.yale.edu/book/9780300224436/water-paradox (accessed on 5 November 2025).

5. Belton, B.; Baldiga, L.; Justice, S.; Minten, B.; Narayanan, S.; Reardon, T. Can the global drone revolution make agriculture more sustainable? Science 2025, 389, 972–976.

6. Drupp, M.A.; Hänsel, M.C.; Fenichel, E.P.; Freeman, M.; Gollier, C.; Groom, B.; Heal, G.M.; Howard, P.H.; Millner, A.; Moore, F.C.; et al. Accounting for the increasing benefits from scarce ecosystems. Science 2024, 383, 1062–1064.

7. Lapworth, D.J.; Baran, N.; Stuart, M.E.; Ward, R.S. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. Environ. Pollut. 2012, 163, 287–303.

8. Barbier, E.B. Water and Economic Growth in Developed and Developing Countries. Water Econ. Policy 2024, 10, 243002.

9. Zhou, S.; Chen, W.; Liu, Y. Can the digital transformation of service trade alleviate global warming? An analysis from the perspective of developing economies. Energy Econ. 2025, 148, 108619.

10. Zeqiri, A.; Ben Youssef, A.; Maherzi Zahar, T. The Role of Digital Tourism Platforms in Advancing Sustainable Development Goals in the Industry 4.0 Era. Sustainability 2025, 17, 3482.

11. Climate Focus. The Voluntary Carbon Market: 2024 Review; Climate Focus: Amsterdam, The Netherlands, 2025; Available online: https://climatefocus.com/wp-content/uploads/2025/01/Voluntary-Carbon-Market-2024-Review.pdf (accessed on 5 November 2025).

12. World Economic Forum (WEF) and McKinsey & Company. Finance Solutions for Nature: Pathways to Returns and Outcomes; World Economic Forum: Cologny, Switzerland; McKinsey & Company: New York, NY, USA, 2025; Available online: https://www.weforum.org/publications/finance-solutions-for-nature-pathways-to-returns-and-outcomes/ (accessed on 9 October 2025).

13. Dowling, R. Global geotourism—An emerging form of sustainable tourism. Czech. J. Tour. 2013, 2, 59–79.

14. Antweiler, W.; Copeland, B.R.; Taylor, M.S. Is free trade good for the environment? Am. Econ. Rev. 2001, 91, 877–908.

15. Zhang, L.L.; Pan, A.; Feng, S.S.; Qin, Y.Y. Digital Economy, Technological Progress, And City Export Trade. PLoS ONE 2022, 17, e0269314.

16. Arcega-Cabrera, F.; Sickman, J.O.; Fargher, L.; Herrera-Silveira, J.; Lucero, D.; Oceguera-Vargas, I.; Lamas-Cosío, E.; Robledo-Ardila, P.A. Groundwater quality in the Yucatan Peninsula: Insights from stable isotope and metals analysis. Groundwater 2021, 59, 878–891.

17. Yasmeen, R.; Tian, T.; Yan, H.; Shah, W.U.H. A Simultaneous Impact of Digital Economy, Environment Technology, Business Activity on Environment and Economic Growth in G7: Moderating Role of Institutions. Heliyon 2024, 10, e32932.

18. Lucero, L.J.; Gunn, J.D.; Scarborough, V.L. Climate change and Classic Maya water management. Water 2011, 3, 479–494.

19. Barbier, E.B.; Burgess, J.C. Economics of Water Scarcity and Efficiency. Sustainability 2024, 16, 8550.

20. Bresciani, S.; Ferraris, A.; Del Giudice, M. The management of organizational ambidexterity through alliances in a new context of analysis: Internet of Things (IoT) smart city projects. Technol. Forecast. Soc. Change 2018, 136, 331–338.

21. Wen, H.W.; Chen, W.J.; Zhou, F.X. Does Digital Service Trade Boost Technological Innovation?: International Evidence. Socio-Econ. Plan. Sci. 2023, 88, 101647.

22. Gozgor, G. Does trade matter for carbon emissions in OECD countries? Evidence from a new trade openness measure. Environ. Sci. Pollut. Res. 2017, 24, 27813–27821.

23. Davenport, T.H.; Guha, A.; Grewal, D.; Bressgott, T. How artificial intelligence will change the future of marketing. J. Acad. Mark. Sci. 2020, 48, 24–42.

24. Trove Research. The Role of "Reduction" and "Removal" Projects in the Voluntary Carbon Market—An Economic Analysis; Trove Research: London, UK, 2023; Available online: https://www.msci.com/www/research-report/the-role-of-reduction-and/04832433783 (accessed on 5 November 2025).

25. Rosegrant, M.W.; Sulser, T.B.; Wiebe, K. Global investment gap in agricultural research and innovation to meet Sustainable Development Goals for hunger and Paris Agreement climate change mitigation. Front. Sustain. Food Syst. 2022, 6, 965767.

26. Hall, C.M. Policy learning and policy failure in sustainable tourism governance: From first- and second-order to third-order change? J. Sustain. Tour. 2011, 19, 649–671.

27. Buera, F.J.; Kaboski, J.P. The rise of the service economy. Am. Econ. Rev. 2012, 102, 2540–2569.

28. Marine Stewardship Council (MSC). The Marine Stewardship Council Annual Report 2020–2021; Marine Stewardship Council: London, UK, 2022; Available online: https://www.msc.org/about-the-msc/reports-and-brochures (accessed on 5 November 2025).