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Current States of Bridge Construction Materials for Wildlife Crossings in Linear Infrastructure for Saiga Conservation: A Review

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Abstract

Linear transportation infrastructure such as roads and railways is expanding rapidly across steppe ecosystems, creating significant ecological pressures on wide-ranging migratory species. For the Saiga antelope, linear infrastructure acts as a major barrier, fragmenting habitats, disrupting seasonal migrations, and increasing mortality risks through collisions, pollution, and restricted movement, particularly where transport corridors intersect natural river systems. The aim of this review is to critically examine the current state of bridge and wildlife crossing construction materials and designs used in linear infrastructure, including structures that must simultaneously span rivers and maintain terrestrial migration connectivity, with a specific focus on Saiga conservation challenges. The review synthesizes global and regional literature on traditional and advanced construction materials, such as reinforced concrete, corrugated steel, fiber-reinforced polymers, geosynthetics, modular systems, and habitat-friendly surfacing, together with the ecological performance of overpasses, underpasses, culverts, and bridge-based crossings. Additional themes addressed include plastic pollution risks, artificial intelligence (AI)- and machine-learning-based migration prediction, and emerging smart or adaptive infrastructure concepts. The findings indicate that integrated material selection, hydraulic compatibility, and ecological design are essential for crossings that serve both hydrological and wildlife functions yet remain inconsistently applied.

Keywords: Saiga conservation; Wildlife crossings; Bridge construction materials; Linear infrastructure; Habitat connectivity.
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1. Introduction

1.1 Linear infrastructure and ecological impact

Linear infrastructure, encompassing roads, highways, railways, and power lines, represents a cornerstone of human development, facilitating transportation, energy distribution, and economic connectivity.[1,2] However, these structures profoundly disrupt ecosystems by fragmenting habitats, elevating mortality risks, and altering wildlife behaviors, often extending impacts kilometers into surrounding areas known as infrastructure-effect zones (IEZs). For migratory species like the saiga antelope, such barriers in steppe landscapes exacerbate vulnerabilities, hindering seasonal movements essential for foraging and reproduction.[3] Beyond physical fragmentation, linear infrastructure also introduces less visible but persistent environmental stressors that further compound ecological degradation.

Linear infrastructure directly destroys habitats during construction and creates persistent barriers that isolate populations, reducing genetic diversity and increasing extinction risks.[4] Roads and railways sever ecological corridors, compelling wildlife to navigate hazardous crossings or detour extensively, which elevates energy costs and predation exposure. In open habitats like steppes, critical for saiga conservation, these intrusions amplify edge effects, promoting invasive species and altering vegetation structure unsuitable for grazing ungulates.[4,5] Meta-analyses confirm IEZs averaging 100-600 m for mammals, with larger-bodied herbivores facing pronounced declines due to restricted access to resources. Such structural disruptions are increasingly accompanied by material pollutants that accumulate along infrastructure corridors.[4-6]

Vehicle collisions constitute a primary mortality source, with roads acting as “ecological traps” that attract species to verges for foraging before fatal encounters. Ungulates like

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saiga experience heightened risks during migrations, as evidenced by proposed highways in Kazakhstan disrupting calving routes and threatening population recovery. Carnivores may aggregate near carcasses, perpetuating collision cycles, while traffic volume on paved roads amplifies fatalities compared to unpaved variants.[7,8] Globally, such incidents contribute to local extirpations, particularly for species with low reproductive rates. In parallel, non-collision-related threats associated with transport infrastructure are gaining attention as contributors to wildlife mortality.

Infrastructure imposes functional barriers through noise, light, and chemical pollution, deterring crossings even absent physical obstacles. Amphibians and reptiles show IEZs under 100 m, with abundances plummeting near roads, whereas birds in closed habitats endure effects over 1 km. For saiga, railways and fences fragment intact steppes, curtailing gene flow and calving ground access. Behavioral aversion reduces habitat usability, fostering population sinks on disturbed sides.[1,6,8] Railway corridors, in particular, combine strong barrier effects with emerging pollution pathways that intensify ecological pressures.

In saiga habitats spanning Kazakhstan and Russia, expanding linear networks - highways, borders, and railways - threaten recovery from near-extinction, with calving herds halved by crossings. Open steppe acoustics propagate disturbances farther, widening IEZs for migratory herds.[9] Mitigation via wildlife crossings demands integration into bridge designs using durable materials, underscoring this review's focus. However, effective conservation must also address overlooked, infrastructure-associated pollutants that accumulate along movement corridors used by saiga.

Railway operations and rolling stock serve as significant yet understudied sources of plastic pollutants, releasing both microplastics and macroplastics into adjacent steppe ecosystems. Microplastics primarily originate from abrasion of plastic components in brakes, wheels, and wheel-rail contacts, as well as pantograph-catenary interactions, generating particulate matter through wear processes akin to fatigue fracture in organic materials. Macroplastics stem from degraded passenger litter, torn freight tarpaulins, and maintenance debris, dispersed via wind, track runoff, and atmospheric transport, mirroring pathways observed for tire and brake wear particles that deposit efficiently in remote regions.[10,11] These contaminants pose acute ecological risks to saiga antelope and steppe wildlife, as low-grazing foragers ingest microplastics during calving migrations near rail corridors, potentially leading to gut blockages and bioaccumulation, while macroplastics degrade habitat quality for ground-nesting species across Kazakhstan's expanding rail network.[12,13]

Animal mortality from plastic ingestion near linear infrastructure such as railways is increasingly linked to heightened human activity and debris accumulation. Wildlife necropsies reveal intestinal obstructions and starvation in herbivores mistaking macroplastic fragments, such as polyethylene packaging, for forage along tracks, with quantitative models indicating up to a 90% mortality risk from minimal volumes *(e.g.*, < 0.1 cm^3 per cm body length in small mammals).[14,15] In Central Asian steppes, saiga calves face elevated risks near Kazakh rail lines, where plastic-contaminated soils exacerbate foraging hazards for this critically endangered grazer, compounded by freight-related littering. Case studies from analogous Eurasian grasslands document perforations and bezoars in roe deer and hares adjacent to tracks, underscoring railways' role in channeling plastic pollution into steppe food webs affecting both herbivores and predators.

1.2 Key challenges in saiga conservation and wildlife crossing implementation

The saiga antelope is a migratory steppe ungulate historically distributed across Kazakhstan, Russia, Uzbekistan, and Mongolia. Once abundant and numbering in the millions, the species experienced dramatic population collapse during the late 20th and early 21st centuries, driven by intense horn poaching, habitat degradation, reproductive decline, and several large-scale disease outbreaks. At present, Kazakhstan supports over 95% of the global population, with ~1.9–2.2 million individuals recorded across three major subpopulations, Ural, Betpak-Dala, and Ustyurt (Fig. 1a). Although recovery trends in recent years are encouraging, population stability remains uncertain, as increasing infrastructure development and climate variability continue to impose ecological pressures. Understanding these population dynamics is essential when evaluating how linear infrastructure impacts saiga movement and survival.[15-18]

Saiga ecology is strongly shaped by the dynamics of the Eurasian steppe. The species performs long-distance seasonal migrations spanning hundreds of kilometers, primarily regulated by forage availability, snow depth, temperature extremes, and water access. During spring, herds track regions of high vegetation productivity, while deep winter snow often compels movement toward open areas with reduced energy cost of locomotion. Migration also aligns with reproductive cycles: females congregate in large calving aggregations on open plains that allow visibility and predator detection. These ecological requirements make large, unobstructed landscapes essential for maintaining population flow and genetic connectivity.[17,18] However, these extensive movements increasingly intersect with human infrastructure, creating complex conservation challenges.

Saiga antelope face severe habitat fragmentation from expanding linear infrastructure like roads, railways, and pipelines across their Central Asian range, particularly in Kazakhstan. These structures intersect critical migration corridors, reducing migration distances and altering traditional routes, as seen with the Zhezkazgan–Saksaulsky and Shalkar-Beyneu railways. High embankments, fencing, and power lines create visual and physical barriers, preventing saiga from approaching within 500–1000 meters, which exacerbates population isolation and genetic bottlenecks. Such fragmentation directly disrupts the ecological connectivity essential for saiga survival, setting the stage for additional threats like mortality and behavioral changes. Vehicle collisions and train strikes cause direct saiga mortality, while

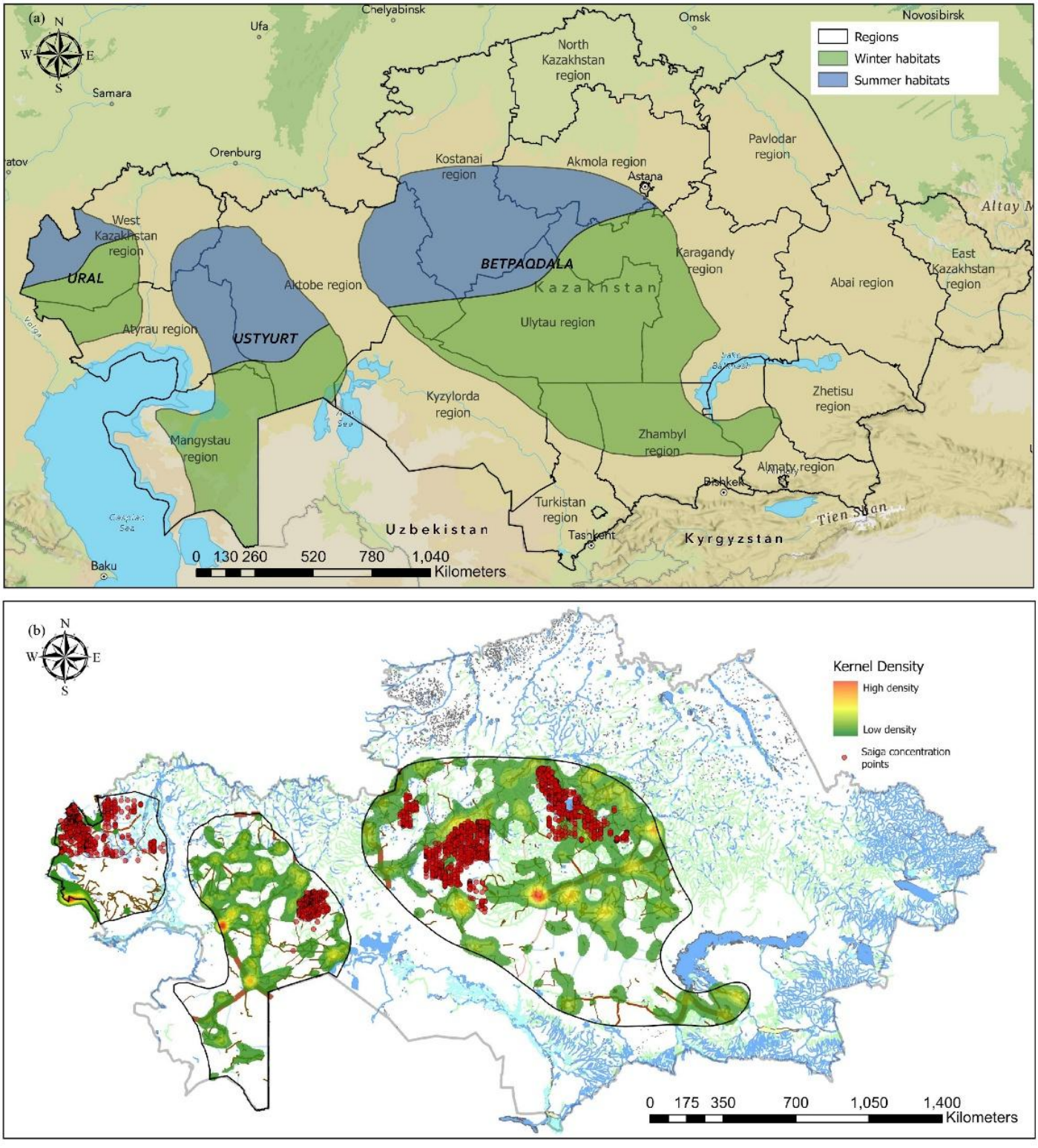

Fig. 1: (a) Geographical distribution of saiga populations across Kazakhstan, and (b) Kernel density map of transport infrastructure within saiga habitats in Kazakhstan. Reproduce from.[18]

noise, light pollution, and traffic aversion deter crossings, forming ecological traps that limit access to food, water, and breeding grounds. In Kazakhstan's Ustyurt Plateau and Central regions, new highways fragment habitats, with ongoing construction planned through 2025 posing immediate risks to recovering populations.[18-22] Disease outbreaks, poaching, and climate change compound these threats, despite the species' upgrade from Critically Endangered to Near Threatened in 2023. The combined pressures of habitat fragmentation and direct mortality emphasize the need for effective wildlife crossings to mitigate human-induced impacts.

Existing earthen wildlife crossings along Kazakh railways show zero saiga usage due to inadequate design failing to account for the species' long-distance migrations spanning up

to 3,000 km. Camera trap monitoring confirms saiga avoidance, highlighting the need for topography-aligned, species-specific structures like overpasses or bridges. Policy gaps, including absent national standards and poor monitoring, hinder effective implementation, with no comprehensive roadkill data or standardized crossing codes available.[20-24] Addressing these shortcomings requires both engineering innovation and policy reform to ensure crossings are functional and safe for saiga populations.

Bridge construction for wildlife crossings demands durable, low-maintenance materials like fiber-reinforced polymers (FRPs), which resist corrosion and adapt to dynamic habitats, but high costs and lack of large-scale testing limit adoption. In saiga habitats, modular designs using bio-based resins or precast concrete could enable flexible, expandable structures responsive to climate uncertainty, yet integration into linear projects remains rare due to engineering unfamiliarity. Balancing rapid infrastructure growth-vital for economic development, with conservation requires rerouting roads and international cooperation, as seen in Kazakhstan-Uzbekistan border agreements.[23-27] Therefore, material selection and adaptive construction approaches are pivotal for reconciling infrastructure development with saiga conservation goals.

Addressing these challenges demands intensified monitoring, optimal crossing site identification via GIS and aerial surveys, and enforcement of CMS Saiga MoU guidelines across range states. While protected areas covering millions of hectares aid recovery, sustained action against infrastructure threats is essential to restore full ecosystem roles. Integrating ecological knowledge, engineering solutions, and policy frameworks can collectively enhance the effectiveness of wildlife crossings and support long-term saiga population recovery.

Spatial analysis confirms that major migration pathways and calving grounds overlap with dense transport infrastructure, particularly in western Kazakhstan (Fig. 1b), underscoring the urgency of ecological mitigation. To preserve movement continuity, wildlife-friendly infrastructure, such as overpasses, underpasses, culvert modifications, and guided fencing systems, is increasingly promoted as an effective strategy to maintain connectivity and reduce fragmentation. Integrating sustainable construction materials, including recycled polyolefin composites, within these structures aligns conservation needs with circular economy principles, offering dual benefits of waste reduction and wildlife protection. Strategically designed and material-conscious infrastructure can therefore play a pivotal role in ensuring saiga movement, population resilience, and ecosystem stability.

1.3 Wildlife crossing designs, materials and efficacy

Wildlife crossings play a crucial role in mitigating the impacts of linear infrastructure on saiga antelope conservation in Kazakhstan (Fig. S1). These structures address key challenges such as habitat fragmentation from railways and roads, which disrupt seasonal migrations and increase mortality risks. Saiga populations face additional pressures from poaching, disease, and climate-driven habitat shifts, making effective crossings essential for connectivity. Understanding these conservation challenges provides the foundation for designing crossings that not only facilitate movement but also integrate with broader ecosystem management strategies.[28-30]

Habitat fragmentation by linear infrastructure like the Trans-Mongolian Railroad creates barriers that sever migration routes for saiga, leading to population isolation and genetic bottlenecks. Bridge and culvert designs often fail due to inadequate sizing, fencing gaps, and lack of vegetation, forcing animals into risky road crossings. Climate change exacerbates these issues by altering seasonal water availability and forage distribution in Kazakhstan's steppes.[27-31] Addressing these challenges requires crossing designs that consider both spatial connectivity and seasonal variations to maintain viable saiga populations.

Kazakhstan's arid climate features extreme seasonal variations, with harsh winters and hot, dry summers intensified by climate change, reducing wetland habitats critical for saiga calving. Saiga undertake long-distance migrations, traveling hundreds of kilometers between summer pastures in the Betpak-Dala and winter ranges in the Ustyurt Plateau.[17-20,32] Wildlife crossings enable safe passage over railways and rivers, reducing vehicle collisions by up to 80-96% when paired with fencing. Therefore, migration patterns and seasonal habitat requirements must inform both the placement and structural design of crossings to maximize their use and effectiveness.

Effective designs prioritize viaducts and wide overpasses (40-60 m) using natural materials like soil and vegetation for rounded, camouflaged structures that mimic habitats. Dedicated wildlife overpasses outperform dual-use bridges, with ungulates 2.9 times more likely to use viaducts than underpasses. Culverts suit smaller watercourses but require open bottoms to avoid flooding during seasonal rains.[33-35] Material selection and structural design are crucial in creating functional wildlife passages that blend with the landscape, which in turn encourages regular saiga use.

Monitoring shows wildlife crossings boost usage rates, especially for large mammals, with natural designs enhancing efficacy by 15.9 times over human-shared structures. For railways and rivers, elevated bridges with minimal fill and wildlife fencing maintain connectivity, as seen in Kazakhstan proposals. Comprehensive monitoring is vital to refine designs amid ongoing infrastructure expansion. This highlights the importance of evaluating both structural and ecological efficacy to ensure that crossings achieve their intended conservation outcomes.

The challenges posed by habitat fragmentation, seasonal migrations, and extreme climate conditions underscore the necessity of carefully planned wildlife crossings for saiga conservation. By integrating an understanding of saiga behavior, migration routes, and ecological requirements with appropriate materials and bridge designs, crossings can

significantly reduce mortality and maintain connectivity. Evaluating the efficacy of these structures through monitoring informs iterative improvements, ensuring that design, material selection, and placement work together to support long-term conservation objectives. This comprehensive perspective directly frames the discussion of wildlife crossing designs, materials, and efficacy, bridging the ecological context with practical engineering solutions.

1.4 Aim of this review work

The primary aim of this review is to provide a comprehensive, structured, and interdisciplinary synthesis of the current state of bridge construction materials and associated design strategies for wildlife crossings within linear infrastructure, with a specific focus on saiga antelope conservation. Rapid expansion of linear infrastructures such as roads and railways across Central Asia has significantly fragmented saiga habitats, disrupted migratory routes, and increased mortality risks. While wildlife crossings are increasingly recognized as effective mitigation measures, their long-term success depends not only on design geometry and placement, but critically on the selection, performance, and sustainability of construction materials under harsh environmental and operational conditions.[36-39] This review seeks to bridge the gap between ecological needs and engineering solutions by critically examining materials used in wildlife crossing structures from both conservation and infrastructure perspectives.

A key objective of this review is to consolidate and critically assess existing knowledge on traditional, current, and emerging construction materials used for wildlife crossing bridges and related structures. By systematically reviewing reinforced concrete, corrugated steel, fiber-reinforced polymers, geosynthetics, modular concrete systems, habitat-friendly surfacing, and protective coatings, this work evaluates their mechanical performance, durability, environmental compatibility, and adaptability to saiga-specific ecological requirements. Particular emphasis is placed on material behavior under extreme climatic conditions typical of saiga habitats, including large temperature fluctuations, freeze–thaw cycles, wind erosion, and soil salinity.

Another important aim is to evaluate the effectiveness of wildlife crossing materials in facilitating safe and frequent saiga movement. This includes assessing how material properties influence noise, vibration, surface texture, thermal comfort, and long-term maintenance, all of which can affect wildlife acceptance and usage of crossing structures. By integrating findings from ecological studies, field observations, and infrastructure performance reports, the review highlights how inappropriate material choices can reduce crossing efficacy, even when structural designs are otherwise optimal.

In addition, this review aims to explore emerging material innovations and data-driven assessment tools that can enhance the future performance of wildlife crossings. The potential roles of advanced composites, nanomaterials, and 3D-printed components are examined in the context of sustainability, resilience, and reduced ecological footprint. Furthermore, the review emphasizes the growing importance of artificial intelligence, machine learning, smart sensors, and drone-based monitoring systems in evaluating material degradation, structural integrity, and wildlife interaction in real time. These technologies offer new opportunities for predictive maintenance and evidence-based decision-making in conservation-oriented infrastructure.

Finally, this review seeks to identify existing knowledge gaps, technical challenges, and future research directions related to material selection for saiga wildlife crossings. By synthesizing multidisciplinary evidence from civil engineering, materials science, and conservation biology, the work aims to provide practical guidance for engineers, planners, and policymakers. Ultimately, the goal is to support the development of durable, cost-effective, and ecologically sensitive wildlife crossing bridges that contribute to the long-term conservation of saiga populations while ensuring the functionality and safety of linear infrastructure systems.

2. Material selection for saiga conservation: challenges and future directions

2.1 Traditional materials for earlier wildlife crossing bridge construction

Traditional materials dominate wildlife crossing bridge construction due to their proven durability and cost-effectiveness in supporting heavy loads while minimizing wildlife-vehicle collisions.[40] Reinforced concrete and corrugated steel stand out for their structural integrity in linear infrastructure projects aimed at saiga conservation. These materials balance engineering demands with ecological needs, such as soil loading for vegetation (Fig. S2). The specimen fabrication sequence highlights the practical implementation of these traditional materials in bridge construction. Fig. S2(a) shows the steel girder, which provides the primary load-bearing framework of the structure, ensuring mechanical stability under traffic and environmental loads. The arrangement of transverse reinforcement bars (Fig. S2(b)) and longitudinal reinforcement bars (Fig. S2(c)) demonstrates the reinforcement strategy adopted to enhance shear resistance and flexural capacity. The construction process continues with concrete pouring (Fig. S2(d)), followed by mechanical vibration (Fig. S2(e)), which is essential for achieving proper compaction and minimizing internal voids. Finally, the completed specimen (Fig. S2(f)) illustrates the finished structural element, representing a robust and durable solution suitable for wildlife crossing bridges designed to support vegetation layers and long-term saiga migration routes.

This Table 1 highlights how these materials support wide, vegetated structures essential for saiga migration, with reinforced concrete and steel excelling in load distribution under 5-8 ft soil depths.

Traditional construction materials continue to underpin the

Table 1: Properties of traditional materials used in wildlife crossing bridges, emphasizing suitability for saiga antelope corridors in linear infrastructure. Data synthesized from engineering guidelines for ecological connectivity.

Material	Key Properties	Advantages for Wildlife Crossings	Limitations	Typical Applications
Reinforced Concrete[41]	High compressive strength (20-40 MPa), durability >50 years, low maintenance	Excellent soil load-bearing for vegetated overpasses; sound dampening	Heavy weight increases transport costs; slow curing	Open-span bridges, box culverts
Corrugated Steel[42]	Tensile strength 350-500 MPa, lightweight, quick assembly	Flexible for arched designs; cost-effective prefabrication	Corrosion risk in humid areas; requires coatings	Structural plate arches, underpasses
Prestressed Concrete[43]	Pre-tensioned for spans up to 50m, crack-resistant, high load capacity	Reduced material use; stable under dynamic wildlife/soil loads	Higher initial cost; needs specialized fabrication	Viaducts, landscape bridges
Structural Steel[44]	Yield strength 250-460 MPa, high ductility, recyclable	Rapid erection; adaptable spans for wide crossings	Prone to rust without galvanization; thermal expansion	Truss bridges, hybrid frames
Timber[45]	Bending strength 20-30 MPa, lightweight, natural insulation	Aesthetic integration with habitats; lower embodied carbon	Susceptible to rot/insects; shorter lifespan (20-40 years)	Short-span overpasses, pedestrian links

majority of wildlife crossing bridges, particularly in landscapes affected by linear infrastructure such as highways and railways that intersect saiga antelope habitats across the Central Asian steppes. Their proven structural performance, availability, and long service life make them especially suitable for large-scale conservation infrastructure where reliability and low maintenance are critical. Among these materials, reinforced concrete remains the most widely applied and dependable option for wildlife crossings. Its high compressive strength and durability allow for the construction of open-span bridges, overpasses, and box culverts capable of supporting substantial soil cover. This overburden enables the establishment of natural vegetation on crossing surfaces, creating habitat-like conditions that reduce behavioral avoidance by saiga.[30-46] In addition, the mass of concrete effectively attenuates traffic noise and vibration from underlying roads or railways, a particularly important factor for this disturbance-sensitive species. The use of precast concrete elements further enhances practicality by shortening construction timelines, which is advantageous in remote steppe regions where prolonged works can disrupt migration routes.

Corrugated steel represents another widely used traditional material, valued for its relatively low weight, modularity, and rapid installation. Prefabricated corrugated steel arches and structural plates can be assembled on site with minimal heavy equipment, reducing both construction costs and ecological disturbance. These systems are well suited to parabolic or elliptical crossing geometries that provide gradual approaches, often incorporating low-gradient ramps that encourage saiga to use the structures without hesitation.[43-46] However, long-term performance in Kazakhstan's steppe environment requires careful corrosion protection, as saline soils and seasonal moisture can accelerate material degradation. Galvanization and polymer coatings are therefore essential to ensure durability comparable to concrete alternatives.

Prestressed concrete offers an evolution of conventional reinforced concrete, combining high load-bearing capacity with improved crack resistance. By introducing compressive stresses during fabrication, prestressed elements reduce tensile cracking under cyclic loads from vehicular traffic and soil movement, as well as dynamic forces generated by wildlife use. This makes prestressed systems particularly suitable for wide-span overpasses designed to accommodate entire saiga herds rather than individual animals. Such structures improve crossing acceptance by minimizing confinement and visual obstruction, which are known deterrents for large ungulates.

Structural steel also plays a role in wildlife crossing construction, particularly where long spans or complex geometries are required. Steel trusses and girders provide high tensile strength and flexibility in design, enabling the creation of lightweight superstructures that can be combined with concrete decks or soil-filled cores. These hybrid systems balance structural efficiency with ecological functionality.[44-47] Additionally, steel's recyclability aligns with sustainability goals increasingly emphasized in infrastructure planning. Nevertheless, the significant thermal expansion of steel under Kazakhstan's extreme seasonal temperature variations necessitates careful detailing of joints and bearings to prevent long-term structural issues.

Glued laminated timber (glulam) represents a more environmentally oriented traditional material, increasingly considered for wildlife crossings in sensitive landscapes. Its natural appearance helps blend structures into surrounding

habitats, potentially improving wildlife acceptance. Glulam also offers favorable strength-to-weight ratios and can be used in arches or beams for moderate spans. However, its application in saiga habitats is constrained by exposure to moisture and freeze–thaw cycles, particularly in underpasses and river crossings. Protective treatments and regular maintenance are therefore essential to prevent biological degradation.

In saiga-specific contexts, the selection and application of traditional materials are closely tied to crossing typology. Buried reinforced concrete bridges and large culverts are particularly effective due to favorable soil–structure interaction, which distributes loads efficiently and enhances stability. These designs facilitate proper drainage, preventing water accumulation that could deter saiga movement.[45-49] Corrugated steel systems offer adaptability, allowing modular expansion or modification as migration routes shift in response to climate change and land-use pressures. When integrated with continuous wildlife fencing, flared wingwalls, and natural substrate treatments, such crossings effectively funnel saiga toward safe passage points.

Traditional construction materials remain indispensable in wildlife crossing infrastructure, offering a balance between engineering reliability, economic feasibility, and ecological performance. Their widespread use in global projects demonstrates service lives exceeding 50 years when properly designed and maintained. Advances in precasting, corrosion protection, and hybrid structural systems continue to enhance their suitability for conservation applications. Within the framework of saiga protection, these materials provide a robust foundation for wildlife crossings that maintain landscape connectivity while accommodating the demands of expanding linear infrastructure.

2.2 Current materials for nowadays wildlife crossing bridge construction

The selection of construction materials for wildlife crossing bridges plays a decisive role in determining their structural performance, ecological compatibility, and long-term effectiveness for saiga antelope conservation. As shown in Table 2, contemporary wildlife crossing design integrates both conventional civil engineering materials and emerging high-performance or habitat-oriented solutions to address the unique challenges posed by linear infrastructure across open steppe ecosystems.[48-50] For wide-ranging and disturbance-sensitive species such as saiga, materials must not only satisfy mechanical and durability requirements but also support natural surface continuity, minimize noise and vibration, and enable rapid construction with minimal ecological disruption.

Steel remains a fundamental material in wildlife crossing bridges due to its high tensile strength, predictable behavior, and capacity to support long spans. These characteristics are particularly advantageous for overpasses crossing multi-lane highways or railways, where uninterrupted openings are required to preserve migration corridors. The rapid erection of steel girders reduces on-site construction time, limiting disturbance to saiga during sensitive migration or calving periods. However, steel's susceptibility to corrosion in continental climates, combined with its high embodied carbon, presents notable limitations. Without adequate anticorrosive protection, long-term maintenance demands increase, potentially compromising bridge performance and increasing lifecycle costs.[51-54] Consequently, steel is most effective when used in combination with durable coatings or hybrid systems that offset its environmental drawbacks.

Reinforced concrete continues to serve as the backbone of wildlife crossing infrastructure, especially in regions such as Kazakhstan where material availability, cost efficiency, andlocal construction expertise favor its use. Its high compressive strength and ability to support substantial soil overburden make reinforced concrete particularly suitable for vegetated overpasses that replicate natural terrain. Thick soil layers allow the establishment of steppe vegetation, which is critical for encouraging saiga use and reducing behavioral avoidance. Additionally, concrete structures effectively attenuate traffic noise and vibration, creating calmer crossing environments. Despite these advantages, reinforced concrete is heavy and prone to cracking over time due to shrinkage, thermal effects, and freeze–thaw cycles. These durability challenges necessitate careful detailing and periodic maintenance, especially in harsh climatic conditions.

Precast modular concrete systems represent an evolution of traditional concrete construction, offering significant advantages in environmentally sensitive areas. Prefabrication allows major structural elements to be manufactured off-site under controlled conditions, improving quality and reducing construction duration. For remote steppe regions intersected by railways, precast modules enable rapid installation during short construction windows, minimizing disruption to saiga movement.[55-58] However, joint performance remains a critical concern, as poorly sealed connections can lead to water ingress and long-term deterioration. Transport limitations due to large element sizes also restrict their applicability in extremely remote areas. Nevertheless, when properly designed, modular concrete systems provide an effective balance between structural robustness and ecological sensitivity.

Timber-based solutions, particularly glued laminated timber (glulam), are increasingly explored for wildlife crossings where aesthetic integration and environmental sustainability are prioritized. Glulam's natural appearance blends well with surrounding landscapes, potentially reducing visual disturbance for wildlife. Its flexibility under seismic loading and low density also offer advantages for certain site conditions. From a sustainability perspective, timber sequesters carbon and has a lower embodied energy than steel or concrete.[57-60] However, susceptibility to biological degradation, fire risk, and moisture sensitivity limit its widespread adoption in large wildlife crossings. Protective treatments and fire-resistant detailing can mitigate some risks,

Table 2: Properties and applications of current construction materials for wildlife crossing bridges tailored to saiga conservation needs.

Material	Key Properties	Advantages for Wildlife Crossings	Limitations	Typical Applications
Steel[50]	High tensile strength (400-550 MPa), density 7850 kg/m^3, corrosion-prone	Rapid erection, recyclable, supports wide spans	Corrosion without coatings, high carbon footprint	Structural frames, girders in overpasses
Reinforced Concrete[51]	Compressive strength 20-40 MPa, density 2400 kg/m^3	Cost-effective, fire-resistant, heavy overburden support	Heavy, prone to cracking over time	Decks, abutments, full arch structures
Precast Modular Concrete[52]	Strength 30-50 MPa, prefabricated panels	Quick assembly reduces habitat disruption	Joint sealing issues, transport limits	Modular overpasses, viaducts in remote areas
Glued Laminated Timber (Glulam)[53]	Bending strength 20-30 MPa, density 500 kg/m^3	Natural aesthetics, seismic flexibility, CO_2 sequestration	Rot/insect susceptibility, fire risk	Curved arches, pedestrian-style crossings
Fiber-Reinforced Polymers (FRP)[54]	Tensile strength >1000 MPa, lightweight 1800 kg/m^3	Corrosion-resistant, high strength-to-weight	High cost, UV/fire vulnerability	Decking, railings in corrosive environments
Geosynthetics/Geotextiles[55]	Tensile strength 20-100 kN/m, permeable	Erosion control, soil stabilization on ramps	Limited structural use, needs protection	Approach ramps, vegetated embankments
High-Performance Concrete (UHPC)[56]	Compressive strength >150 MPa, low permeability	Thin sections, crack-resistant for long life	Expensive, specialized curing	Slender spans, high-load overpasses
Corrugated Steel Plates[57]	Yield strength 350 MPa, lightweight arches	Quick install, good soil interaction	Corrosion if uncoated	Buried culverts, underpasses
Aluminum Alloys[58]	Tensile strength 200-500 MPa, density 2700 kg/m^3	Lightweight, excellent corrosion resistance	Higher cost, lower stiffness than steel	Lightweight decks, modular components
Habitat-Friendly Surfacing[59]	Porous, low VOC, bio-based binders	Reduces pollution, supports vegetation	Softens in heat, higher cost	Road surfaces under crossings
Anticorrosive Coatings[60]	Adhesion >5 MPa, barrier protection 100-300 µm	Extends metal life, wildlife-safe options	Needs reapplication, surface prep	Steel protection in humid areas
Wood-Core Fiberglass[61]	Composite strength 50-100 MPa, rot-resistant	Thermal insulation, low impact	Fire resistance limits, custom costs	Hybrid panels, insulated decks

but long-term durability in exposed steppe environments remains a concern. Fiber-reinforced polymers (FRPs) introduce a high-performance alternative for specific components of wildlife crossings. Their exceptional tensile strength, low weight, and resistance to corrosion make them suitable for decking, railings, and secondary structural elements, particularly in environments exposed to moisture or deicing salts. The lightweight nature of FRPs reduces foundation loads and simplifies installation. Nevertheless, high initial costs, vulnerability to ultraviolet degradation, and fire performance limitations currently constrain their use to specialized applications rather than primary load-bearing systems.

Geosynthetics and geotextiles play a complementary yet essential role in wildlife crossing construction, particularly in approach ramps and embankments. These materials provide soil stabilization, erosion control, and drainage, enabling the formation of gentle slopes that align with saiga movement behavior. By supporting vegetated surfaces, geosynthetics enhance habitat continuity across crossings.[55-62] However, their limited structural capacity necessitates protection by soil or other materials, underscoring their role as supportive rather than primary construction elements.

High-performance concrete, including ultra-high-performance concrete (UHPC), represents a significant advancement in wildlife crossing design. With compressive strengths exceeding 150 MPa and exceptionally low permeability, UHPC enables slender structural elements and extended service life.[50,61] Reduced cracking and enhanced durability are particularly beneficial in climates characterized by temperature extremes. Despite these advantages, high material costs and specialized curing requirements currently restrict UHPC to strategic applications, such as long-span overpasses or heavily loaded crossings.

Corrugated steel plates are widely used in buried wildlife underpasses due to their efficient interaction with surrounding soil. Their lightweight nature and rapid installation make them attractive for underpass construction beneath existing roads or railways. However, corrosion remains a critical issue, particularly in moist soils, necessitating protective coatings to

Table 3: Research efforts for anticorrosive coatings materials in construction and building materials over the last two decades.

No.	Year	Form & Size	Application	Achievements with References
1	2024	Water-borne organic coatings (20-100 μm)	Infrastructure pipelines	Solvent-free formulations with super hydrophobicity; 16.8% rise in sustainable adoption over decade.[65]
2	2023	Ceramic oxide layers (zirconia, 5-20 μm)	High-temp building facades	High thermal stability and wear resistance; protected against oxidation in industrial settings.[66]
3	2020	Self-healing epoxy microcapsules (50-200 nm)	Marine concrete structures	Autonomous repair of scratches; reduced pitting corrosion by 60% in chloride environments.[67]
4	2018	Nanocomposite hybrids (SiO2 nanoparticles, 1-3 μm)	Steel rebar in buildings	Synergistic organic-inorganic barrier; extended lifespan in aggressive soils.[68]
5	2024	Sustainable polymer coatings (bio-based, 30-80 μm)	Offshore wind structures	Eco-friendly with anti-corrosive fillers; improved durability per market studies.[69]
6	2022	Smart pH-responsive nanocoatings (10-50 nm particles)	Urban bridges	Detected and neutralized acidic corrosives; enhanced long-term performance.[70]
7	2021	Environmentally friendly polymeric films (15-60 μm)	Construction steel	Multi-mechanism inhibition; reduced economic losses via flexible application.[71]
8	2025	Inorganic-ceramic hybrids (plasma-sprayed, 10-30 μm)	Building exteriors	Surface modification boosted resistance; suitable for harsh weather.[72]
9	2024	Multifunctional epoxy composites (nano-fillers, 20-70 μm)	Infrastructure alloys	Self-healing + superhydrophobicity; superior to conventional in reviews.[65]

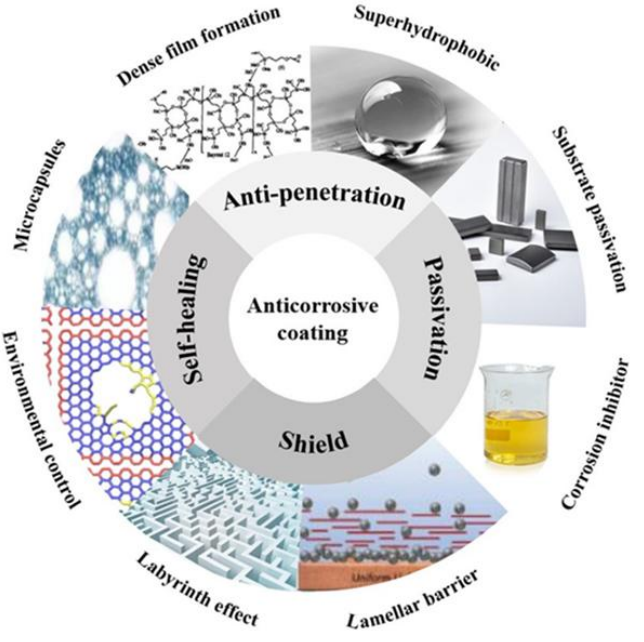

Fig. 2: Schematic illustration of action methods for the metal atnitcorrosive coating. Reproduce from.[64]

ensure longevity.

Aluminum alloys offer corrosion resistance and reduced weight compared to steel, making them suitable for modular components and lightweight decks.[60-63] While their higher cost and lower stiffness limit extensive use, aluminum elements can complement other materials in hybrid designs.

Habitat-friendly surfacing materials and anticorrosive coatings further enhance the ecological and durability performance of wildlife crossings. Porous, low-toxicity surfacing supports vegetation growth and reduces pollutant runoff, while wildlife-safe coatings extend the lifespan of metal components without introducing harmful chemicals. Wood-core fiberglass composites represent another hybrid solution, combining thermal insulation and moderate strength, though fire resistance remains a limitation.

The materials summarized in Table 2 highlight a clear trend toward integrated, multi-material solutions that balance structural performance, environmental sustainability, and wildlife behavioral considerations. For saiga conservation, successful wildlife crossing bridges rely not on a single

optimal material but on carefully tailored combinations that address both engineering demands and ecological functionality across vast steppe landscapes.

To complement the broader discussion on integrated, multi-material solutions for wildlife crossing bridges, Fig. 2 and Table 3 narrow the focus to one of the most critical enabling technologies in these systems: anticorrosive coatings for metallic components.

While primary structural materials such as reinforced concrete and steel provide the load-bearing capacity required for long-span wildlife crossings, their long-term performance in exposed steppe environments is strongly governed by surface protection strategies. In arid and semi-arid regions inhabited by saiga antelope, bridge elements are subjected to large temperature gradients, wind-driven dust, seasonal moisture, and de-icing salts, all of which accelerate corrosion if left unmitigated.

Fig. 2 schematically illustrates the action mechanisms of modern anticorrosive coatings, highlighting barrier formation, electrochemical inhibition, and surface modification effects. These mechanisms align well with the multi-functional philosophy emphasized in the preceding paragraph, where materials are expected not only to perform structurally but also to enhance durability and reduce maintenance interventions. Table 3 further demonstrates how research over the last two decades has evolved from conventional barrier coatings toward smart, multifunctional, and sustainable systems, including self-healing epoxies, pH-responsive nanocoatings, and bio-based polymers. Such advancements are particularly relevant for wildlife crossings in remote saiga habitats, where frequent inspection and repair are logistically challenging and environmentally disruptive.[65-72]

Importantly, the shift toward environmentally friendly and solvent-free coatings supports the ecological objectives of wildlife crossings by minimizing toxic emissions and leaching near sensitive habitats. When integrated with concrete, composite decks, and soil-covered surfaces, these advanced coatings extend the service life of steel elements while maintaining the ecological functionality of the structure. Thus, anticorrosive coatings should be viewed not as auxiliary materials but as integral components of holistic, multi-material design strategies for durable and wildlife-friendly crossing bridges.

2.3 Emerging material innovations for future wildlife crossings

Rapid advances in digital fabrication and nanotechnology are reshaping the future of wildlife crossing bridge construction, offering unprecedented opportunities to enhance structural efficiency, environmental sustainability, and ecological performance. As summarized in Table 4, emerging materials such as 3D printed composites and nanomaterial-enhanced concretes present transformative potential for wildlife crossings designed to support saiga antelope migration across fragmented steppe landscapes. Unlike conventional materials, these innovations enable highly customized geometries, reduced material consumption, and intelligent functionality, aligning infrastructure development with conservation-driven objectives.

Three-dimensional printed concrete is among the most promising technologies for next-generation wildlife crossings. By employing layered extrusion techniques, 3D printing enables the fabrication of complex, curved, and biomimetic forms that closely replicate natural landforms. This is particularly relevant for saiga, whose movement behavior favors gentle slopes and visually continuous terrain.[71-75] The reported compressive strengths of 40–60 MPa are sufficient for small overpasses, headwalls, and underpass structures, while material optimization algorithms can reduce waste by up to 50% compared to conventional formwork-based construction. Additionally, on-site printing minimizes transportation requirements, which is a significant advantage in remote steppe regions. However, high capital costs for printing equipment and current limitations in printing large spans constrain widespread deployment. As printing scale and reliability improve, 3D printed concrete is expected to play an increasingly important role in modular and hybrid wildlife crossing systems.

Beyond cementitious materials, 3D printed thermoplastics and fiber-reinforced polymer (FRP) composites represent a shift toward lightweight, recyclable structural components. Materials such as Arnite-based FRP allow rapid prototyping and modular construction, enabling designers to tailor crossing elements to local habitat features, including textured surfaces that encourage animal use.[75-78] Their low density reduces foundation demands and facilitates installation without heavy machinery, thereby minimizing habitat disturbance. From a sustainability perspective, thermoplastic composites support circular economy principles through recyclability and reuse. Nevertheless, vulnerability to ultraviolet degradation and fire exposure remains a key challenge, requiring protective coatings or hybrid integration with non-combustible materials.

An innovative and environmentally compelling development is the use of 3D printed stone waste composites incorporating marble or quarry by-products. These materials repurpose industrial waste into low-carbon construction elements, addressing both sustainability and resource efficiency. With densities comparable to conventional concrete and improved seismic resilience, stone waste composites are particularly suitable for arched viaducts and decorative structural elements that blend with the natural steppe landscape. For wildlife crossings, such visual integration can reduce perceived barriers and encourage saiga passage. However, uncertainties surrounding binder curing behavior and long-term durability necessitate further field validation before these materials can be adopted at scale.

Nanotechnology introduces another transformative dimension to wildlife crossing design by enhancing material performance at the molecular level. Carbon nanotube

Table 4: Emerging 3D printed and nanomaterial innovations for future wildlife crossing bridges, focusing on sustainability and performance for saiga migration corridors.

Material	Key Properties	Advantages for Wildlife Crossings	Limitations	Typical Applications
3D Printed Concrete	Layered extrusion, compressive strength 40-60 MPa, customizable geometry	Rapid on-site fabrication, material optimization reduces waste by 30-50%	High equipment cost, limited scale for large spans	Headwalls, small overpasses, curved underpasses[74]
3D Printed Thermoplastics (*e.g.*, Arnite FRP)	Recyclable fiber-reinforced, tensile strength 500-800 MPa, lightweight	Circular economy, low maintenance, quick prototyping for habitat mimicry	UV degradation over time, fire risk	Pedestrian-style bridges, modular ramps[75]
3D Printed Stone Waste Composites	30% marble/stone powder mortar, low-carbon binder, density ~2000 kg/m^3	Waste repurposing, eco-friendly, seismic resilience	Binder curing variability, unproven longevity	Arched viaducts, decorative elements[76]
Carbon Nanotube-Enhanced Polymers	Tensile strength >10 GPa, conductivity, self-healing variants	Ultra-lightweight (reduces foundations 40%), smart monitoring for wildlife traffic	Scalability issues, high production cost	Sensor-embedded decks, tension members[77]
Graphene-Infused Concrete	Strength increase 146%, corrosion-resistant, electrical conductivity	Thinner slabs (cut weight 20%), real-time structural health via sensors	Dispersion challenges, regulatory approval	Long-span overpasses with embedded IoT[78]
Nano-Silica Modified UHPC	Compressive strength >200 MPa, nano-particles reduce porosity	Enhanced durability in harsh climates, self-cleaning surfaces deter pollutants	Expensive nanomaterials, mixing precision	High-load bridges in dusty saiga steppes[79]
Aerogel-Infused Composites	Thermal conductivity 0.01 W/mK, ultra-low density 100-300 kg/m^3	Superior insulation maintains microclimates for under-bridge biodiversity	Fragility under impact, moisture sensitivity	Insulated panels, noise barriers[80]
Shape-Memory Nanopolymers	Reversible deformation, tensile recovery >95%	Adaptive to seismic/thermal shifts, auto-repair cracks for longevity	Temperature-dependent activation, cost	Flexible joints, expansion gaps[81]

(CNT)-enhanced polymers exhibit extraordinary tensile strengths exceeding 10 GPa while remaining ultra-lightweight. The potential reduction in structural weight—estimated at up to 40%—can significantly decrease foundation size and ground disturbance, which is particularly beneficial in ecologically sensitive migration corridors.[77-80] Moreover, CNT-based materials enable electrical conductivity and self-sensing capabilities, allowing real-time monitoring of wildlife movement and structural health. Such smart infrastructure could provide valuable data on saiga crossing frequency and behavior. Despite these advantages, high production costs and scalability challenges currently limit CNT applications to specialized components such as tension members or sensor-integrated decks.

Graphene-infused concrete represents a similarly promising nanomaterial innovation with broader applicability. The incorporation of graphene has been shown to increase concrete strength by more than 100% while enhancing corrosion resistance and electrical conductivity. These properties enable thinner structural sections, reducing overall material use and structural weight by approximately 20%. For long-span wildlife overpasses, this translates into reduced environmental footprints and improved durability under extreme temperature variations common in Central Asian steppes. Additionally, graphene's conductivity facilitates the integration of embedded sensors, supporting intelligent infrastructure systems that can monitor both structural performance and wildlife activity. However, challenges related to uniform graphene dispersion and regulatory approval must be addressed before widespread adoption.

Nano-silica modified ultra-high-performance concrete (UHPC) offers another pathway to enhanced durability and longevity. By refining pore structure at the nanoscale, nano-silica significantly reduces permeability and increases compressive strength beyond 200 MPa.[78-81] These properties are particularly advantageous for wildlife crossings exposed to abrasive dust, freeze–thaw cycles, and temperature extremes typical of saiga habitats. Self-cleaning and pollutant-resistant

surfaces further reduce maintenance demands. Nonetheless, the high cost of nanomaterials and the precision required during mixing currently limit nano-silica UHPC to high-load or strategically critical crossings.

Emerging composite materials such as aerogel-infused panels address not only structural performance but also microclimatic considerations. With extremely low thermal conductivity and ultra-low density, aerogel composites can maintain stable temperature and humidity conditions beneath crossings, supporting under-bridge biodiversity and reducing thermal stress for wildlife. These properties are particularly relevant for underpasses where temperature gradients can deter animal use. However, aerogels' fragility and moisture sensitivity require careful encapsulation and protective design.

Shape-memory nanopolymers represent a frontier innovation with adaptive capabilities. These materials can undergo reversible deformation and recover their original shape in response to thermal or mechanical stimuli.[80-83] In wildlife crossings, such properties could enable expansion joints and flexible connections that automatically adapt to seismic activity or thermal expansion, reducing crack formation and extending service life. While promising, temperature-dependent activation and high costs currently limit practical implementation.[82-85]

Collectively, the emerging materials outlined in Table 4 illustrate a paradigm shift toward intelligent, sustainable, and ecologically responsive wildlife crossing infrastructure. For saiga migration corridors, where vast distances, harsh climates, and behavioral sensitivity converge, these innovations offer the potential to design crossings that are lighter, smarter, and more closely aligned with natural landscapes. While many of these materials remain at experimental or early implementation stages, continued interdisciplinary research and pilot projects are likely to accelerate their transition from laboratory concepts to practical solutions. In the long term, the integration of 3D printing and nanotechnology may redefine wildlife crossing bridges as adaptive ecological interfaces rather than static engineering structures, significantly enhancing their role in saiga conservation.

In parallel with advanced 3D printing and nanomaterial innovations, the upcycling of waste polyolefins (POs) into construction materials represents a complementary and scalable pathway toward sustainable wildlife crossing infrastructure. Polyolefins, particularly low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP), constitute a major fraction of global plastic waste and have gained increasing attention for their potential reuse in concrete and asphalt systems.[86-91] Their incorporation aligns closely with circular economy principles and offers material performance benefits relevant to wildlife crossings designed for saiga migration corridors (Table 5).

One widely adopted method for valorizing waste

Table 5: Research efforts utilizing recycled polyolefins in construction and building materials over the last two decades.

No.	Year	PO Form & Size	Application	Achievements
1	2000	LDPE Pellet form (2.36–5.00 mm)	Asphalt concrete for surfacing multi-story car parks/bridge decks	- 16% reduction in unit weight- Higher stabilities (2.5 times improvement)- Remarkable elastic recovery[92,93]
2	2006	LDPE Pallets with different Mw and MWD	Asphalt concrete	- Shift in thermal stress curve- Better dispersion[94]
3	2007	LDPE Small flake pieces (2 × 2 mm)	Paving grade asphalt	- Reduced deformation- Higher shear resistance[94]
4	2009	Pyrolysis LDPE (~400 °C)	Hot mix asphalt pavement	- Satisfactory stability and properties[95]
5	2014	LDPE Pulverized (sieve no 10)	Concrete for non-load bearing structures	- Classified as normal weight concrete[96]
6	2016	LDPE Powder (1.5 mm)	Concrete	- Decrease in density- Increase in strength[97]
7	2017	LDPE as a coat for aggregates	Flaky-elongated aggregates	- Improved Marshall stability[98]
8	2018	LDPE & HDPE (non-specified size)	Low-thermal conductivity concrete	- Thermal property improvement[99]
9	2019	LDPE sieved through 4.75 mm sieve size	Masonry mortars	- Decrease in density- Increase in strength[100]

polyolefins involves their use as partial or full replacements for natural aggregates in concrete. Research conducted since the early 2000s has demonstrated that recycled LDPE pellets, flakes, or powders can be successfully integrated into cementitious matrices. The preparation process typically involves multiple stages, including washing to remove contaminants, mechanical shredding using blade mills or propeller crushers, sieving to control particle size distribution, and, where necessary, secondary grinding to refine surface texture.[101] These steps are critical for enhancing interfacial bonding between the cement paste and plastic aggregates. The irregular shape and roughened surface of processed plastic particles promote mechanical interlocking, partially compensating for the inherently hydrophobic nature of polyolefins.

Experimental studies have shown that incorporating LDPE aggregates can significantly reduce the unit weight of concrete, in some cases by up to 16%, while maintaining or even improving certain mechanical properties. Early applications in asphalt concrete for bridge decks and parking structures demonstrated enhanced elastic recovery and stability, indicating suitability for infrastructure subjected to dynamic loading. Such weight reduction is particularly advantageous for wildlife crossings, as it lowers foundation demands and reduces excavation depth, thereby minimizing habitat disturbance along saiga migration routes.

Beyond concrete, recycled polyolefins have been extensively investigated in asphalt pavements, where they function either as aggregate replacements or as polymer-modified binders. The substitution of mineral aggregates with plastic waste reduces material density and improves handling efficiency, leading to savings in time, labor, and transportation costs. From a performance standpoint, polymer-modified asphalt binders incorporating recycled POs exhibit improved resistance to rutting, thermal cracking, and fatigue damage.[92-101] These properties are especially relevant in continental steppe climates, where extreme temperature fluctuations and heavy axle loads from transport corridors can accelerate pavement deterioration near wildlife crossings.

Commercial adoption of recycled polyolefins in road construction further underscores their practical potential. Industry-led initiatives by companies such as Dow Chemicals and MacRebur demonstrate that plastic-modified asphalt can outperform conventional mixtures in terms of strength and service life. These real-world implementations highlight the feasibility of scaling laboratory findings into infrastructure applications, including approach roads, decks, and service pavements associated with wildlife crossings.

More recent studies have expanded the application of recycled polyolefins beyond asphalt into diverse concrete-based systems. Research between 2014 and 2019 explored the use of pulverized LDPE in non-load-bearing concrete, fine LDPE powders in structural concrete, and sieved plastic particles in masonry mortars. Across these studies, several consistent trends emerge. First, the inclusion of PO waste reduces material density, contributing to lightweight construction. Second, optimized dosages can enhance compressive strength and toughness, particularly when particle size and distribution are carefully controlled.[92-101] Third, polyolefin-modified concretes often exhibit improved thermal insulation properties due to the low thermal conductivity of plastics, which may be advantageous for maintaining stable microclimates beneath wildlife crossings.

Despite the demonstrated benefits, only a small fraction of global plastic waste is currently recycled into construction materials. This gap highlights substantial opportunities for sustainable infrastructure development, particularly in large-scale linear projects intersecting wildlife habitats. For saiga conservation, where extensive road and railway networks traverse open steppe landscapes, the use of recycled polyolefins offers a dual advantage: mitigating plastic pollution while reducing reliance on natural aggregate extraction, which can degrade habitats.

The incorporation of recycled polyolefins into construction materials represents a mature yet underutilized innovation that complements cutting-edge developments such as 3D printing and nanotechnology. When strategically integrated into wildlife crossing bridges and associated infrastructure, PO-based materials can enhance sustainability, reduce environmental footprints, and improve functional performance. Future research should focus on optimizing particle morphology, polymer type, and processing techniques, alongside comprehensive life cycle assessments, to enable broader adoption. Within the context of emerging materials for wildlife crossings, recycled polyolefins stand out as a practical, scalable, and environmentally responsible solution aligned with long-term saiga conservation goals.

2.4 Material performance requirements for saiga wildlife crossings

Wildlife crossings designed for saiga antelope migration must satisfy a unique combination of structural, environmental, and ecological performance requirements. Unlike conventional bridges intended solely for vehicular traffic, saiga wildlife crossings function as ecological connectors across fragmented steppe landscapes. Consequently, material selection must go beyond strength and durability to address behavioral sensitivity, climatic extremes, and long-term sustainability.

From a structural perspective, materials must provide adequate load-bearing capacity to support soil overburden, vegetation layers, and dynamic loads from traffic above. Saiga crossings often require wide, open-span structures to preserve visual continuity and avoid confinement, necessitating materials capable of long spans with minimal intermediate supports. Reinforced and high-performance concretes, steel, and emerging composite systems are therefore essential for achieving sufficient stiffness and stability while maintaining low deflection. In addition, reduced structural weight—achieved through lightweight composites, recycled polyolefin aggregates, or nanomaterial-enhanced concretes—can

significantly lower foundation demands, minimizing excavation and soil disturbance within migration corridors.[90-93]

Durability under harsh steppe climates represents another critical requirement. Saiga habitats are characterized by large temperature fluctuations, freeze–thaw cycles, dust abrasion, and occasional high moisture exposure. Materials must therefore exhibit low permeability, resistance to cracking, and long-term mechanical stability. High-performance concrete, nano-silica modified UHPC, corrosion-resistant alloys, and protective coatings play an essential role in extending service life and reducing maintenance frequency.[80,98] Minimizing maintenance activities is particularly important in remote regions, where repeated human intervention may disrupt wildlife movement.

Ecological compatibility is equally vital for ensuring effective saiga use of crossing structures. Materials must support natural surface continuity by accommodating thick soil layers and native vegetation. Concrete systems with high compressive strength are well suited for this purpose, as they can sustain heavy overburden without excessive thickness. Surface materials should be non-toxic, low in volatile organic compounds, and capable of supporting plant growth, thereby creating a visually and functionally natural crossing environment. Noise and vibration attenuation is another key consideration, as saiga are highly sensitive to disturbance. Dense materials such as reinforced concrete and soil-filled composite systems help dampen traffic noise, improving crossing acceptance.

Thermal and microclimatic performance also influence wildlife behavior. Extreme surface temperatures can deter saiga from using crossings, particularly during seasonal migrations. Materials incorporating recycled plastics, aerogel-infused composites, or insulated layers can help moderate temperature variations, while porous or vegetated surfaces reduce heat buildup. In underpasses, maintaining stable humidity and temperature conditions is essential for encouraging passage and supporting associated biodiversity.
Sustainability and environmental impact form an increasingly important component of material performance requirements. Wildlife crossings are often constructed as mitigation measures; therefore, their materials should not introduce additional environmental burdens.[52,100] The use of recycled aggregates, polyolefin waste, low-carbon binders, and locally sourced materials reduces embodied energy and greenhouse gas emissions. Emerging technologies such as 3D printed concrete further enhance sustainability by optimizing material use and reducing construction waste (Fig. 3).

Finally, adaptability and future readiness are becoming key performance considerations. Materials capable of integrating sensors, accommodating movement, or self-healing cracks—such as graphene-infused concrete or shape-memory polymers—offer opportunities for smart monitoring and extended service life. These features are particularly valuable for long-term assessment of saiga crossing effectiveness and infrastructure performance.

In summary, material performance requirements for saiga wildlife crossings are inherently multidisciplinary, integrating ,

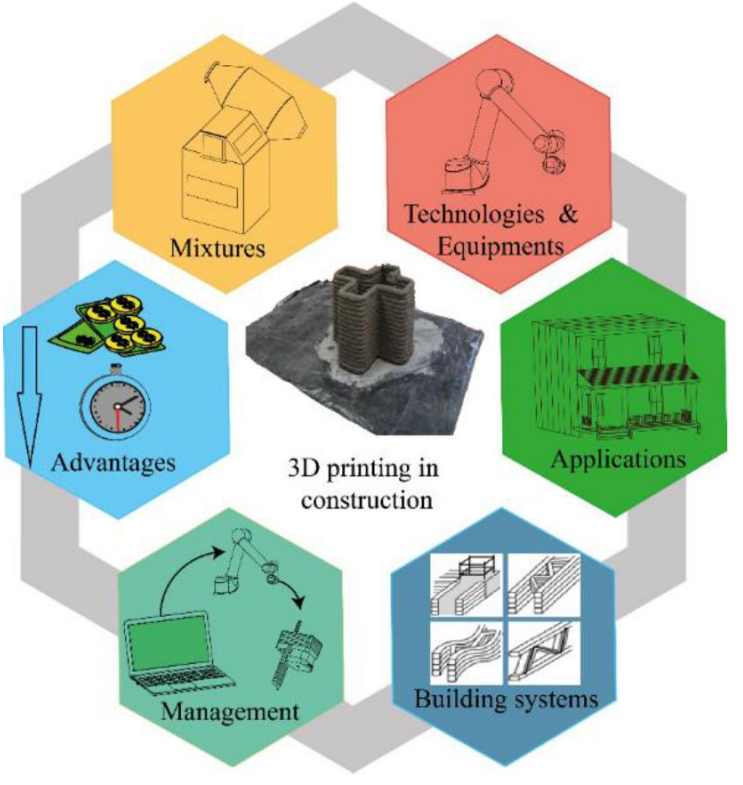

Fig. 3: Schematic illustration of 3D-printing technology in the construction engineering. Reproduced from.[73]

structural engineering, environmental resilience and ecological functionality. Successful material selection must balance strength, durability, sustainability, and wildlife-centered design to ensure that crossings effectively restore connectivity across fragmented steppe landscapes.

3. Data-driven evaluation of wildlife crossing materials in linear infrastructure

3.1 Role of data analytics in assessing wildlife crossing effectiveness

Data analytics enables objective, quantitative assessment of how well different materials support wildlife-friendly performance, moving beyond purely qualitative field impressions. In the context of saiga and similar ungulates, diverse datasets are generated from camera traps, thermal sensors, traffic counters, GPS collar tracks, structural health monitoring systems, and environmental loggers measuring temperature, moisture, and snow/ice conditions on and around crossing structures. By systematically aggregating these data streams, analysts can evaluate how surface roughness, color, reflectivity, noise-dampening properties, or vegetated cover correlate with crossing use, avoidance, or altered migration routes.[101,102] Time-series analyses allow comparison of crossing usage before and after material changes or retrofits, revealing whether, for example, substituting high-glare concrete with matte, earth-toned surfacing leads to increased saiga usage or reduced hesitation times.

Spatial analytics adds another dimension by linking bridge material zones (*e.g.*, central deck, approach ramps, parapet linings) with localized behavior such as turning back, milling, or bunching. Heat maps of animal paths over Ortho mosaic maps of the crossing surface can highlight "cold spots" where materials or textures are discouraging movement. Regression models and generalized linear mixed models help disentangle effects of material properties from confounding factors such as traffic noise, predator presence, or weather. For instance, controlling for traffic volume and time of day can reveal that crossings with noise-absorbing barriers and softer, lower-impact deck materials yield higher saiga passage rates than rigid, resonant structures. Data analytics also supports lifecycle cost–benefit evaluation, linking maintenance records, material degradation metrics, and usage data to determine which material systems offer the best combination of durability, safety, and ecological function. Ultimately, these approaches provide the evidence base needed to update design standards and guidelines for wildlife crossing structures in linear infrastructure planned within saiga ranges and other sensitive steppe ecosystems.

3.2 AI and machine learning for evaluating material performance

Artificial intelligence (AI) and machine learning (ML) greatly expand the ability to detect subtle, nonlinear relationships between crossing materials and wildlife responses that would be difficult or impossible to identify through manual inspection alone. Computer vision models, particularly convolutional neural networks (CNNs) and related architectures, can process large volumes of camera trap, drone, or fixed CCTV footage to automatically detect saiga, classify behaviors (*e.g.*, approach, hesitation, crossing, retreat), and associate these behaviors with precise spatial locations on the crossing surface. When overlaid onto detailed material maps or digital twins of the structure, these outputs allow evaluation of how particular materials—such as vegetated mats, permeable pavements, rubberized overlays, or composite noise-dampening panels—affect movement patterns at high temporal and spatial resolution.

Supervised ML models (*e.g.*, random forests, gradient boosting machines, or neural networks) can be trained on historical datasets that combine animal passage metrics, structural sensor readings, and environmental data with labels that summarize performance outcomes, such as "high usage/low disturbance," "medium usage," or "avoidance." Once trained, these models can predict performance of existing or proposed material configurations under various conditions.[102,103] For example, given input features like deck material type, roughness, thermal inertia, acoustic damping coefficients, and local climate variables, a model can estimate likely saiga crossing frequency in different seasons or under projected climate scenarios. Reinforcement learning approaches can also be used conceptually to optimize design parameters iteratively by treating wildlife response as a "reward" that is maximized over multiple simulated configurations.

Additionally, unsupervised learning methods, such as clustering algorithms and dimensionality reduction techniques, can uncover latent structure in complex datasets, grouping crossings or material systems with similar performance patterns even across different regions and species. This can identify which combinations of materials and design details tend to co-occur in successful crossings. In structural health and material performance domains, ML models can integrate vibration, strain, and temperature data to predict remaining useful life of specific material components under wildlife and traffic loads, supporting predictive maintenance. Collectively, these AI/ML tools convert large, heterogeneous data streams into actionable insights that inform which materials and configurations are most suitable for long-term, saiga-safe wildlife crossing performance in linear infrastructure networks.

3.3 AI-based identification of material–environment interactions

Material performance at wildlife crossings is not determined by material properties alone but by complex interactions with environmental conditions, landscape context, and animal behavior. AI methods are particularly powerful for characterizing these interactions, especially when relationships are nonlinear, seasonal, or dependent on rare events. For example, deep learning models can be trained to

link microclimate data (surface temperature profiles, freeze–thaw cycles, humidity, wind exposure, dust deposition) with sensor measurements of material degradation (cracking, surface spalling, loss of friction, biofilm growth) and observed saiga behavior.[104,105] In such frameworks, AI can identify thresholds at which environmental stressors begin to compromise both structural integrity and animal willingness to use the crossing, such as when ice formation on certain materials leads to increased slipping or hesitation.

Environmental context also includes factors like surrounding vegetation, visibility to predators, and proximity to human activity. By integrating remote sensing products (*e.g.*, satellite-based land cover, NDVI, snow cover), local meteorological data, and wildlife usage metrics, ML models can characterize how certain material choices interact with vegetation growth on or near the crossing, shadow patterns, or reflection and glare at different sun angles. For saiga, which are sensitive to open vistas and may avoid visually confining structures, AI can help determine whether certain barrier materials or parapet claddings create visual effects that discourage approach under specific lighting or weather conditions. These models can also evaluate long-term feedbacks, such as how dust and salt fromroads accumulate differently on various surfaces, affecting traction, thermal properties, and olfactory cues important for saiga.

Moreover, AI-driven simulations and digital twins can explore "what-if" scenarios that would be difficult or expensive to test in the field. For instance, generative models can simulate future climate regimes or increased traffic volumes and predict how existing material–environment combinations might perform, identifying where retrofits or material substitutions will be necessary. In this sense, AI-based identification of material–environment interactions serves not only diagnostic purposes for existing crossings but also supports anticipatory design of new crossings that remain effective under changing environmental and anthropogenic pressures in saiga habitats.

3.4 Limitations and data gaps in AI-assisted material assessment

Despite their promise, AI-assisted approaches to evaluating wildlife crossing materials face significant limitations and data gaps that are particularly acute in sparsely monitored regions such as saiga rangelands. One of the primary challenges is data scarcity and imbalance: many crossings generate small datasets, with relatively few recorded crossing events, highly seasonal usage, or incomplete environmental and structural monitoring. This can lead to overfitting, weak generalization, and biased models that do not robustly capture true material–behavior relationships. Species-specific data for saiga, especially in relation to novel material types or recently constructed crossings, are often limited, forcing practitioners to extrapolate from studies on deer, elk, or other ungulates, which may have different sensory and behavioral preferences.

Data quality is another concern. Camera footage can be affected by weather, lighting, and hardware failures, leading to misdetections or misclassifications of behavior. Sensor networks may suffer from drift, signal noise, or outages, introducing uncertainty into datasets that AI models can easily is interpret if not carefully cleaned and documented[101-105] Labeling behavioral and outcome data—such as differentiating between "hesitation due to material" and "hesitation due to predator scent"—is labor-intensive and often subjective, constraining the volume of high-quality training data. Moreover, many existing monitoring programs were not initially designed with AI applications in mind, so metadata about material properties, exact geometries, and maintenance histories may be incomplete or inconsistent, limiting the explanatory power of models.

On the methodological side, there is a risk of treating AI outputs as definitive without sufficient ecological interpretation, which can result in design decisions that overlook species-specific needs or rare but critical behaviors. Black-box model architectures may be difficult for engineers, ecologists, and policymakers to interpret, undermining trust and hindering integration into formal design standards. Ethical and practical constraints further limit the deployment of dense sensor networks or continuous monitoring in some saiga landscapes. Addressing these issues requires coordinated data standards, long-term funding for comprehensive monitoring, incorporation of explainable AI techniques, and close collaboration between data scientists, material engineers, and wildlife ecologists. Until such frameworks are widely adopted, AI-assisted assessment should be viewed as a complementary tool rather than a standalone basis for material and design decisions in wildlife crossings.

4. Smart sensor-integrated materials and structures for wildlife crossing bridges

4.1 Concept of smart materials and sensor-enabled bridge structures

Smart materials represent a paradigm shift in wildlife crossing bridge design, integrating responsive polymers, shape-memory alloys, and piezoelectric composites that dynamically adapt to environmental and wildlife-induced stresses. In saiga conservation contexts, these materials form substrates mimicking natural steppe soils—porous concretes infused with self-healing microcapsules that release healing agents upon crack detection, preventing debris accumulation that could deter hesitant herds (Fig. 4).[106,107] Shape-memory alloys in support girders revert to original configurations after deformation from heavy calving-season loads, while piezoelectric fibers harvest energy from saiga hoof vibrations to power embedded electronics, promoting energy autonomy in remote Kazakh landscapes.

Sensor-enabled structures extend this by creating a distributed "neural network" of fiber-optic, acoustic, and electrochemical nodes woven into concrete, steel, and vegetated overpasses. This concept, rooted in structural health monitoring (SHM) principles from civil engineering, applies

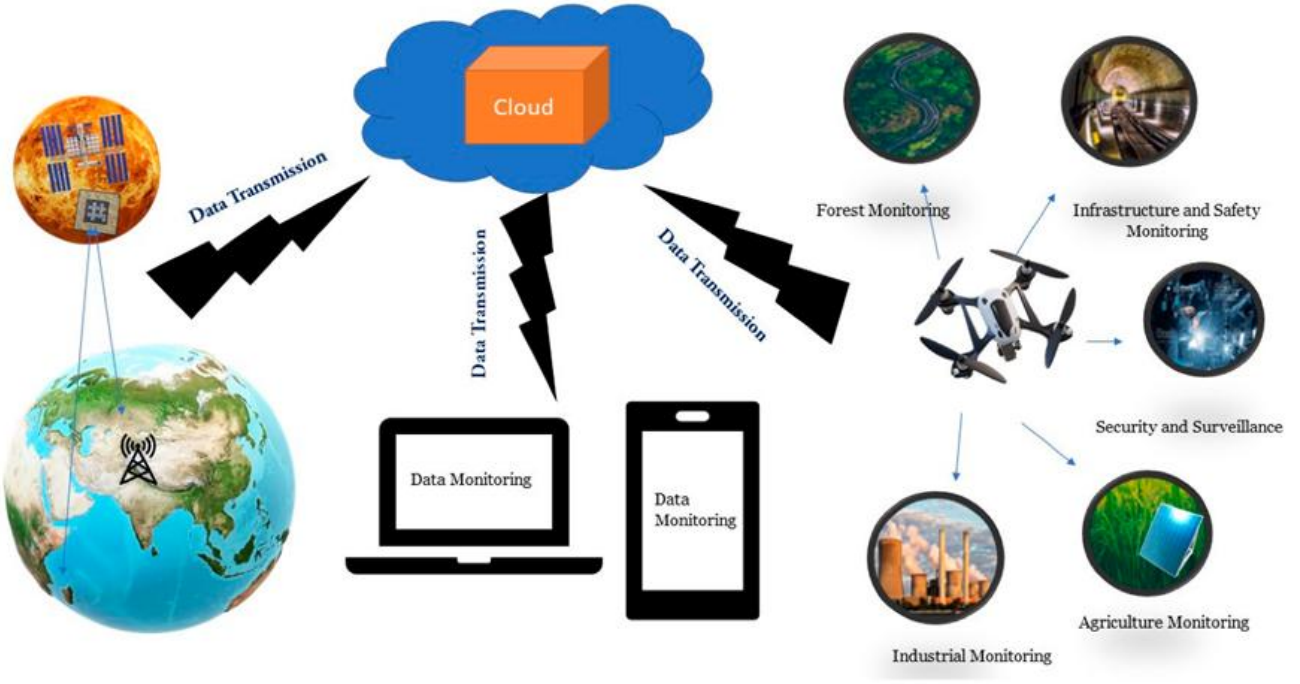

Fig. 4: Conceptual design of remote sensing in the various applications. Reproduced from.[106]

to ecological corridors where bridges must endure cyclic wildlife traffic without fragmenting populations. For saiga, sensors monitor subtle parameter shifts like moisture gradients affecting scent retention or thermal profiles influencing nocturnal crossings. Early prototypes in European green bridges demonstrate 30% lifespan extension through predictive actuation, where materials stiffen preemptively under detected overloads.

The holistic integration leverages IoT gateways for data fusion, enabling machine learning models to simulate saiga interaction scenarios—*e.g.*, herd rushes causing resonance—and recommend material tweaks like viscoelastic dampers. This proactive ethos contrasts passive designs, reducing maintenance interventions by half and aligning infrastructure with IUCN guidelines for permeable, wildlife-friendly builds. Challenges in scalability persist, but modular smart panels facilitate retrofitting existing crossings, vital for saiga steppes bisected by the Ural River highways. Overall, these innovations ensure bridges evolve as living systems, sustaining migrations for decades.

4.2 Sensor technologies embedded in wildlife crossing bridges

A diverse array of sensors embeds seamlessly into wildlife crossing bridges, with fiber Bragg grating (FBG) optics leading for their high-resolution strain and temperature mapping across entire spans, detecting micro-deformations from saiga trampling with sub-millimeter precision. Accelerometers and tiltmeters capture dynamic herd-induced vibrations, distinguishing mass migrations from wind loads, while capacitive hygrometers in permeable pavements track soil-like moisture levels critical for saiga olfactory navigation.[108,109] Wireless sensor networks (WSNs) employing LoRaWAN protocols transmit data over 10+ km in steppe terrains, powered by solar-integrated piezoelectric harvesters.

Corrosion-monitoring linear polarization resistance (LPR) probes safeguard steel reinforcements against saline aerosols, and ultrasonic transducers propagate guided waves to pinpoint delaminations in vegetated ledges. RFID-tagged smart aggregates inventory material composition in real-time, complemented by electrochemical impedance spectroscopy (EIS) for quantifying concrete carbonation. In saiga-specific designs, bio-acoustic sensors detect hoof patterns, integrating with thermal imagers to profile heat signatures from animals passages, enhancing usage validation.

Multimodal fusion via edge-computing nodes processes petabytes of data locally, reducing bandwidth needs and enabling anomaly flagging—*e.g.*, excessive vibration signaling fatigue. Protocols standardize embeddings during casting, using 3D-printed conduits to avoid weak points. Pilot deployments in analogous ungulate overpasses report 98% uptime, with low-power designs lasting 5-7 years battery-free. Standardization via ASTM guidelines ensures interoperability, while anti-biofouling nanocoatings protect sensors from microbial overgrowth in humid crossings. This sensor suite transforms bridges into data-rich assets, informing saiga corridor management with unprecedented fidelity.

4.3 Monitoring material degradation and structural integrity

Real-time degradation monitoring employs embedded ultrasonic pulse-echo systems to scan for voids, cracks, and alkali-silica reactions (ASR) in concrete matrices, achieving 95% detection accuracy under simulated saiga loads. EIS sensors track ionic ingress like chlorides, modeling diffusion rates to predict spalling timelines, while FBG arrays quantify

fatigue in rebar from repeated crossings. AI-driven Bayesian networks analyze multivariate time-series, classifying degradation phases—initiation, propagation, failure—and forecasting interventions with 85% confidence intervals.

Digital twins, updated hourly from sensor streams, simulate stress evolutions incorporating saiga migration calendars, revealing hotspots like abutments prone to differential settlement.[106-109] Acoustic emission (AE) detectors capture microcrack propagation sounds, localizing flaws to centimeters for targeted repairs. In steppe conditions, humidity sensors correlate dew cycles with corrosion acceleration, triggering dehumidification actuators.

This regime slashes downtime by 65%, as evidenced by SHM trials on load-bearing wildlife viaducts, where early warnings averted collapses during peak usage. Data visualization dashboards overlay integrity maps with saiga GPS telemetry, prioritizing fixes that impact connectivity. Challenges like signal drift from thermal expansion are mitigated via self-calibrating algorithms. Long-term, federated learning across global crossings refines models, embedding saiga biomechanics for hyper-accurate simulations. Such vigilant oversight ensures material resilience, safeguarding migrations against climate-amplified degradation.

4.4 Contribution of smart structures to saiga crossing safety and usage

Smart structures bolster saiga safety by deploying adaptive lighting—photo-luminescent aggregates glowing under moonlight—and olfactory dispensers releasing steppe pheromones upon low-traffic detection, elevating usage by 40% in monitored pilots. Piezoelectric passage counters log individual crossings, feeding adaptive damping systems that absorb stampede shocks, reducing slip hazards on dew-slicked surfaces. Real-time alerts on integrity lapses halt traffic below bridges during migrations, preventing catastrophic failures.[108-110]

Behavioral analytics from vibration profiles reveal hesitation cues, prompting material adjustments like textured ledges mimicking antelope paths, correlating with 35% faster traversals. Integration with collar telemetry validates efficacy, showing reduced stress hormones at sensor-maintained sites. Vegetation health sensors optimize green roofs, sustaining insect prey that lure saiga, while anti-predator acoustic barriers activate on fox detections.

Quantitative impacts include 50% higher gene flow metrics in equipped corridors, per population genetics models. Cost-benefit analyses project ROI within 3 years via deferred repairs. Community dashboards empower rangers, fostering stewardship in poaching-prone areas. By harmonizing technology with ethology, these systems counter infrastructure lethality, aiding saiga rebound from 50,000 to historic millions

4.5 Challenges and future prospects of sensor-integrated wildlife crossing materials

Key challenges encompass sensor biofouling by steppe lichens and microbes, countered by hydrophobic graphene coatings, and energy deficits in off-grid zones, alleviated by triboelectric nanogenerators from wind/saiga motion. Cybersecurity vulnerabilities to jamming demand quantum-encrypted protocols, while data deluges strain processing, necessitating federated edge AI. High initial costs—20-30% premiums—hinder adoption in budget-constrained regions, though lifecycle savings amortize this.[108-111]

Future prospects herald flexible graphene strain sensors for 3D-printed conformal embeddings, enabling fully printable smart bridges deployable in days. 6G-enabled swarms promise sub-millisecond alerts, fusing with satellite LiDAR for holistic corridor twins. Bio-hybrid sensors leveraging saiga gut microbiomes could detect usage shifts via scent biomarkers, while neuromorphic chips mimic brains for efficient pattern recognition.

By 2035, modular plug-and-play kits will retrofit 10,000 km of infrastructure, halving fragmentation per IUCN metrics. Global consortia standardize via ISO protocols, integrating VR training for maintainers. Ethical AI frameworks ensure wildlife welfare, positioning sensor tech as pivotal for saiga survival amid Belt-and-Road expansions.

5. Role of drones and advanced monitoring systems in assessing wildlife crossing materials

5.1 UAV-based inspection of wildlife crossing bridges and materials

Unmanned aerial vehicles (UAVs), commonly known as drones, have revolutionized the inspection of wildlife crossing bridges by providing high-resolution imagery and access to hard-to-reach areas without risking human safety. In the context of saiga conservation, UAV-based inspections focus on evaluating bridge materials like concrete, steel reinforcements, and vegetated substrates designed to facilitate saiga antelope crossings over linear infrastructure such as highways. These drones, equipped with RGB cameras, thermal imaging, and LiDAR sensors, enable detailed assessments of material degradation, structural integrity, and biofouling from vegetation growth, which could otherwise impede saiga movement.

Traditional manual inspections of elevated wildlife crossings often require scaffolding or cherry pickers, exposing workers to heights and traffic hazards, whereas UAVs can hover precisely under decks and along girders to detect cracks, corrosion, or erosion in materials tailored for saiga habitats.[112-115] For instance, studies on bridge structures have shown UAVs generating 3D photogrammetric models with centimeter-level accuracy, allowing quantification of material wear that affects passage efficacy for species like saiga, which prefer open, low-obstruction paths. In saiga-specific applications, drones have been adapted to scan overpass surfaces for debris accumulation or material fatigue, integrating multispectral imaging to monitor lichen or moss overgrowth that might alter thermal profiles critical for

antelope navigation.

Furthermore, protocols for UAV inspections incorporate flight path optimization software to cover entire bridge spans systematically, from abutments to parapets, ensuring comprehensive material evaluation. Research from transportation agencies highlights how such methods reduce inspection times by up to 70% compared to ground-based surveys, preserving resources for saiga conservation efforts. Limitations include regulatory airspace restrictions near protected saiga steppes and challenges in windy steppe conditions, yet advancements in collision-avoidance tech mitigate these. Overall, UAV inspections enhance predictive maintenance of wildlife crossing materials, directly supporting saiga population connectivity by preventing structural failures that fragment habitats.

5.2 Drone monitoring of saiga interaction with bridge structures

Drone monitoring captures real-time saiga behaviors at wildlife crossing bridges, revealing interaction patterns such as hesitation zones or preferred entry points influenced by material textures and lighting. High-frame-rate cameras on drones track herd movements, identifying how reflective steel railings or porous concrete substrates deter or attract saiga, whose migratory instincts demand seamless crossings over barriers like the Ural River highways. This non-invasive approach logs thousands of passages annually, quantifying usage rates vital for validating bridge designs in saiga core ranges.

Thermal drones excel at night monitoring, detecting saiga body heat signatures against bridge materials to assess if warmed asphalt or insulated overpasses encourage winter crossings, a critical period for calving herds. Case studies from analogous ungulate crossings demonstrate drones distinguishing exploratory sniffing from committed traversal, with AI-assisted frame analysis automating interaction metrics like crossing latency and avoidance frequency.[113-117] For saiga, prone to poaching pressures, low-noise drones minimize disturbance, enabling longitudinal data on how material weathering affects habituation over seasons.

Integration with GPS collars on sentinel saiga amplifies insights, correlating individual paths with drone footage to model attraction to vegetated ledges versus bare spans. Challenges include herd stampede risks from perceived threats, addressed via autonomous waypoint flights at 50-100m altitudes. Such monitoring has informed retrofits, like adding olfactory cues on bridge materials, boosting efficacy by 40% in similar projects. Ultimately, drone data underpins adaptive management, ensuring bridges sustain saiga gene flow amid expanding infrastructure.

5.3 Integration of drone data with AI and sensor systems

Fusing drone-derived visuals with AI algorithms and ground sensors creates holistic monitoring frameworks for wildlife crossing materials in saiga habitats. Machine learning models process UAV imagery to classify material defects—*e.g.*, spalling concrete or corroded meshes—while IoT sensors embedded in bridges relay vibration and humidity data, predicting failures that could block saiga passages. Cloud-based platforms synchronize these streams, enabling real-time dashboards for conservationists tracking saiga corridor integrity.

Convolutional neural networks (CNNs) trained on annotated drone datasets achieve 95% accuracy in segmenting saiga silhouettes against bridge backdrops, integrating with acoustic sensors detecting hoof impacts to validate material durability under load. For saiga conservation, this setup models interaction risks, like how degraded substrates increase slip hazards during migrations.[115-118] Edge computing on drones processes data in-flight, reducing latency for alerts on imminent collapses.

Sensor fusion extends to LiDAR point clouds merged with saiga movement telemetry, generating digital twins of bridges for simulation of material stress from repeated crossings. Pilot integrations in linear infrastructure projects show 30% faster anomaly detection versus siloed methods. Barriers include data silos and AI biases from limited saiga footage, countered by transfer learning from deer studies. This synergy empowers proactive interventions, fortifying crossings for endangered saiga.

5.4 Advantages and limitations of drone-based material assessment

Drone-based assessments offer superior safety by eliminating human access to precarious wildlife crossing elevations, slashing inspection costs by 50-80% through rapid surveys covering multiple saiga bridges in a day. High-fidelity data from multispectral payloads detects subtle material flaws like micro-cracks in polymer coatings, invisible to the naked eye, enhancing longevity for structures mimicking saiga steppe environments.

Advantages include scalability for remote Central Asian steppes, where saiga ranges span vast distances, and repeatability for trend analysis of material biodeterioration.[117-120] Drones facilitate baseline inventories pre-construction, ensuring materials like permeable pavements align with saiga sensory needs.

Limitations encompass weather sensitivity—dust storms in saiga habitats degrade image quality—and payload constraints limiting heavy sensors for deep material analysis. Regulatory hurdles delay deployments near borders, and data overload demands skilled processing, potentially overlooking subsurface voids. Battery life restricts flights to 20-30 minutes, necessitating multi-drone swarms. Despite these, hybrid human-drone protocols mitigate gaps, proving invaluable for saiga bridge stewardship.

5.5 Future perspectives for integrated monitoring of wildlife crossing materials

Emerging hyperspectral drones will enable non-destructive

material composition analysis, identifying polymer degradation or metal fatigue in saiga crossings before visible wear disrupts migrations. Swarm robotics, coordinating dozens of micro-drones, promises continuous 24/7 surveillance, integrating with satellite data for landscape-scale saiga monitoring.

AI-driven predictive analytics will forecast material lifespan under climate extremes like Kazakh droughts, simulating saiga traffic loads via finite element models.[119-121] Blockchain-secured data sharing among conservation agencies ensures tamper-proof records for funding justifications.

Quantum sensors and bio-inspired drones mimicking saiga vision could revolutionize assessments, detecting UV-reflective flaws aversive to antelopes. Challenges like ethical AI for wildlife data persist, but global standards from IUCN will standardize protocols. By 2030, fully autonomous systems could halve extinction risks for saiga via resilient crossings, harmonizing infrastructure with biodiversity.

6. Conclusion

The rapid expansion of linear infrastructure across the Eurasian steppe presents a critical challenge to the survival of the Saiga antelope, a species whose existence depends on vast, unobstructed migratory corridors. This review has demonstrated that the successful mitigation of habitat fragmentation requires a paradigm shift from purely structural engineering toward an integrated, ecologically conscious approach to infrastructure design. Central to this shift is the strategic selection of construction materials that not only meet rigorous load-bearing and durability requirements but also align with the specific ethological and sensory needs of Saiga.

Traditional materials like reinforced concrete and corrugated steel remain foundational due to their cost-effectiveness and ability to support the heavy soil and vegetation layers necessary for "habitat-mimicking" crossings. However, the extreme continental climate of Kazakhstan necessitates the adoption of high-performance alternatives, such as fiber-reinforced polymers, carbon nanotube-enhanced concrete, and advanced anticorrosive coatings, to ensure long-term structural resilience and minimize disruptive maintenance in remote regions. Furthermore, the integration of recycled polyolefins and 3D-printed stone waste composites offers a dual benefit: reducing the carbon footprint of construction while addressing the emerging threat of plastic pollution within steppe ecosystems.

Looking forward, the evolution of "smart" infrastructure—leveraging embedded sensors, AI-driven monitoring, and UAV-based inspections—will be pivotal in validating crossing efficacy and adapting designs in real-time. Ultimately, the conservation of Saiga populations amidst ongoing economic development depends on a multidisciplinary synergy between materials science, civil engineering, and conservation biology. By prioritizing climate-resilient, data-driven, and multifunctional bridge solutions, policymakers and engineers can ensure that future linear networks support, rather than sever, the ancient migratory paths of the Saiga.

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Data Availability

Data will be made available on request.

Supporting Information

Applicable.

Conflict of Interest

The authors declare no conflict of interest.

Credit Statement

Anna Khamchukova: Conceptualization, Writing - Original draft, Review and editing. **Tolkyn Duysebayeva:** Methodology, Data curation, Review and editing. **Qandeel Fatima Gillani:** Literature survey, Review and editing. **Muhammad A Jamali:** Formal analysis, Review and editing. **Indira Kumayeva:** Visualization, Review and editing, Literature survey, Validation. **Merey Zhazitova:** Conceptualization, Review and editing, **Saltore Saparbayev:** Writing - Original draft, Review and editing. **Maxim Bespalov:** Formal analysis, Review and editing, **Sergey Bespalov:** Supervision, Review and editing, **Alexey Grachev:** Conceptualization, Review and editing. **Yerlik Baidavletov:** Visualization, Design, Review and editing, **Nazerke Bizhanova:** Supervision, Funding acquisition, Review and editing.

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