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REVIEW

Subsurface Integrity at the Energy-Environment Interface: Advances in Ground Construction for Oil and Gas Storage and Transport Systems

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ABSTRACT

The integrity of the subsurface at the energy environment interface is essential for the safe, long-term and responsible storage and transportation of oil and gas. The latest developments in materials, design techniques, and monitoring systems have revolutionized the design and operation of subsurface infrastructure in a manner that employs simultaneous solutions to mechanical, chemical, and geotechnical problems. The case in this review is the state-of-the-art developments in the subsurface construction, storage system, and transport network, including high-performance alloys, geopolymers, composite linings, and bio-mediated stabilization systems. The adaptive structural designs, such as reinforced foundations, multi-layer linings, and flexible pipeline systems, enhance resilience during conditions of a difference in settlement, cyclic loading, and geochemical exposure. By using fiber-optic sensing, digital twins, and machine learning, predictive management and monitoring help detect a possible failure on time and optimize the interventions in the operations. The environmental safeguards are also critically assessed in the review, such as erosion control, groundwater protection, and sustainable construction practices, focusing on how they are integrated with operational and regulatory goals. The shortage of geological predictability, material behavior over long periods, and adjustment to new energy sources, including hydrogen and CO_2, are stated, and future research and practice directions are outlined. The article highlights the necessity of a multidisciplinary approach that is holistic, showing that the key to resilient, sustainable, and safe subsurface energy infrastructure is integrated

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engineering, materials, and monitoring strategies that can address energy and environmental demands as they change.

Keywords: Subsurface Integrity; Oil and Gas Storage; Pipeline Transport; Geotechnical Engineering; Monitoring and Predictive Management

1. Introduction

Integrity of subsurface systems is one of the subjective criteria in the safe, efficient, and environmentally responsible storage and transportation of oil and gas[1,2]. The modern supply networks of energy are based on subsurface infrastructure, such as pipelines, storage caverns, tanks, and foundation systems[3,4]. These systems should be capable of handling highly complicated mechanical, chemical, and environmental pressures throughout long working periods[5]. The engineering design has traditionally been concerned with the mechanical integrity and the working stability of these infrastructures. Nevertheless, the growing need for environmentally responsible energy management, compounded with increased environmental scrutiny, has increased the value of subsurface integrity at the energy–environment interface. This concept is not only limited to structural strength, but also to environmental compatibility, leakages, and geotechnical stability in the long term[6].

In the past, underground failures at oil and gas storage systems and transportation systems have caused disastrous environmental impacts such as groundwater pollution, soil erosion, and emission of greenhouse gases[7]. Well-publicized pipeline releases, cave falls, and ground settlements have highlighted the limitations of the traditional approaches to construction and monitoring methods. Such incidents have led regulatory bodies and industry participants to introduce a higher level of standards of subsurface integrity, which necessitated the development of new materials, construction methods, monitoring, and maintenance plans[1,8]. Here, the discipline is experiencing a paradigm shift in that the subsurface engineering practice will involve environmental sustainability, resilience, and risk reduction as part of an integrated energy-environment approach to design.

The holistic approach to the integrity of the subsurface is one of the new facets of this review. Although earlier research has tended to look at either geotechnical stability, pipeline engineering, or materials performance, the review brings together these fields to bring forth the interdependence of mechanical, chemical, or environmental variables[9]. By doing so, it captures the multidisciplinary developments that are transforming the ground construction practice of oil and gas systems. This encompasses the development of new materials, such as high-performance geopolymers and composite liners, and anti-corrosion finishes, which enhance durability without having negative effects on the environment[10]. It also includes the ground stabilization methods, such as chemical treatment of the soil, bio-mediated processes, which increase the load-bearing capacity and minimize the propensity of the sub-ground to deform[11].

The other major novelty of this review is the emphasis on monitoring, predictive modeling, and digital integration. The use of real-time sensing and geophysical imaging coupled with enhanced data analytics is becoming more and more important in modern subsurface integrity management to predict the mechanisms of failure even before they can undermine the safety of operations[12]. Fiber-optic, borehole acoustic, and 3D geomechanical modeling techniques give the first-ever visualization of the conditions in the subsurface[13]. This review can show how the combination of monitoring technologies and innovative construction techniques can increase safety and environmental stewardship by combining these developments. In addition, the use of artificial intelligence and digital twins in predictive modeling is a revolutionary trend as it allows operators to model scenarios, plan maintenance operations, and reduce the environmental risk ahead[14].

The review is also dedicated to the development of both storage and transport systems of civilization and how innovations in construction are applied to definite use in the subsurface[15,16]. Geomechanical problems in underground storage include salt caverns, depleted reservoirs, and aquifers, which have distinct geomechanical requirements that require special engineering solutions. In the case of pipeline networks, trenchless technologies, cathodic protection, and adaptive coating systems have come into existence to increase the service life and reduce environmental impact. This review presents cross-cutting innovations by contrasting the developments in storage and transport systems to inform best practices in the sector. The focus on environmental protection, such as slope stabilization, erosion control, and groundwater protection, emphasizes the growing importance of considering the interrelation between the subsurface engineering process and environmental protection[17].

The other important work of this review is its prospective view on sustainability and energy transition. With the world developing energy systems that are more sensitive to renewable energy, carbon capture and storage (CCS), and hydrogen transport, there are new demands on the infrastructure of the subsurface[18]. Materials and construction technologies should be made resilient not only to traditional oil and gas activity, but also to the new multi-energy activity. This review gives a critical synthesis of how modern subsurface integrity strategies can be modified to these new environments to make sure that both storage and transport systems are robust, safe, and environmentally compatible in changing operational and regulatory environments[19].

Lastly, the goal of this review is to fill the gap between the management of environmental responsibility and engineering innovation. It gives a synopsis and covers the state of the art in subsurface integrity management by incorporating recent developments in materials, construction methods, monitoring, and sustainability[20]. The article does not just focus on technical performance but highlights the implications for environmental protection, regulations, and operational resilience in the long term. It is an important refinement of the traditional reviews that view mechanical and environmental analyses independently, providing a more comprehensive theory for further research, design, and policy formulation.

To conclude, the novelty of this review is that, in a multidisciplinary and prospective synthesis of subsurface integrity at the energy-environment interface, the review has been carried out. It brings to the fore: (i) new materials and construction processes that increase durability and environmental friendliness; (ii) new monitoring, sensing, and predictive modeling principles; (iii) application-specific innovations in storage and transport systems; and (iv) approaches to include sustainability and resilience in subsurface engineering[21–24]. In this way, the review will allow the creation of a state-of-the-art reference.

2. Fundamentals of Subsurface Integrity

Subsurface integrity is a multidimensional concept that forms the foundation of the safe and efficient functioning of the oil and gas storage and transportation systems[25]. It is not only the structural and mechanical soundness of the subsurface infrastructure but also the geotechnical stability of the infrastructure, its chemical resistance, and compatibility with the environment during extended periods of operation. The role of underground integrity has increased over recent years due to the growth of environmental questioning, the stringency of regulations, and the necessity to make energy systems flexible to meet the demands of climate change mitigation measures. Subsurface infrastructure failures such as pipeline bursting, collapse of storage caverns, and foundation settlements have all proven that the traditional design methods that only emphasized mechanical strength are inadequate[26]. It is therefore important that the fundamentals of mechanisms that control subsurface integrity are fully understood to come up with robust energy infrastructure.

2.1. Conceptual Framework of Subsurface Integrity

Subsurface integrity has, at its fundamental level, three dimensions that are interrelated, namely, mechanical, chemical, and geotechnical. **Figure 1** presents the conceptual model of subsurface integrity that demonstrates how mechanical, chemical, and geotechnical dimensions interrelate and impact storage and transport systems. Mechanical integrity is the ability of the structure (a pipeline, the foundation of a storage tank, a lining of a cavern) to resist the forces exerted on the structure without failure or undue deformation of the structure[27]. This dimension has long been the major factor in engineering design, and material strength, structural redundancy, and load distribution are very strong. Yet, the special focus on the mechanical properties does not always account for others, like the interactions with the environment or soil-structure interaction, which may trigger a failure despite the fact that the materials are not in the design limits[26].

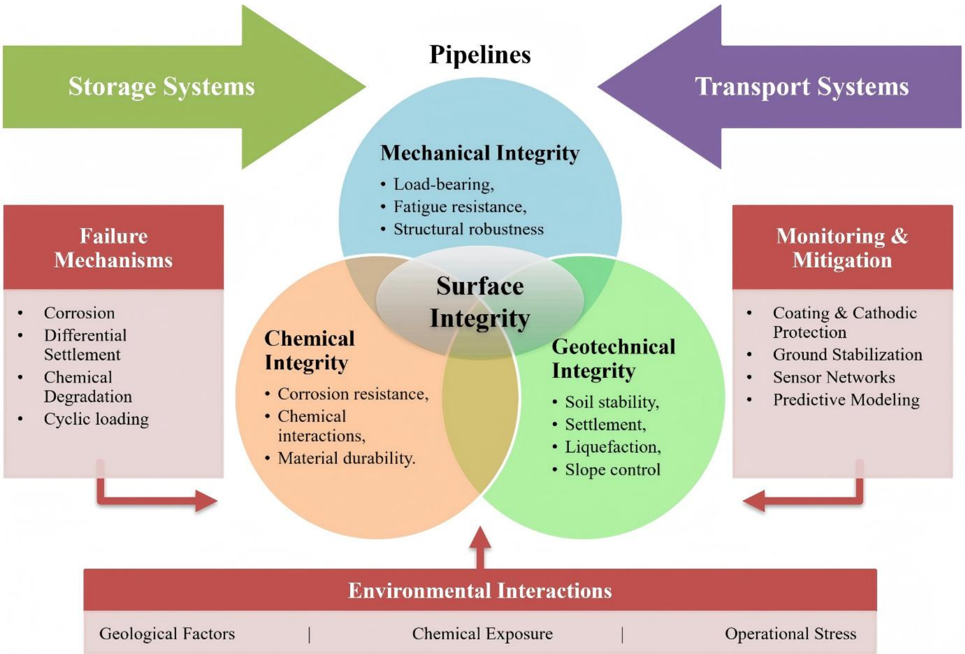

Figure 1. Conceptual framework of subsurface integrity, illustrating mechanical, chemical, and geotechnical interactions.

Chemical integrity primarily provides resistance of building materials and the soils that surround them against reactive processes that can undermine stability[27]. The subsurface materials have to be in complicated chemical surroundings, such as aggressive ions, hydrocarbons, and groundwater that has an unstable pH and salinity. These interactions may cause corrosion, leaching, or degradation of materials, causing microfractures and leakage paths. The chemical aspect is increasingly being identified as not only an issue in the field of material science, but also a key component of risk assessment, especially considering the environmental impact of hydrocarbon emissions to soils or aquifers.

Geotechnical integrity is the stability of the ground itself, which includes the soil strength, permeability, the consolidation behavior, and the deformation propensity[28]. Underground structures are not static in relation to the masses in the soil and rocks, but occur as a result of the movement of the earth mass, and the failures are usually not predetermined by the structural frailty. Storage and transport systems may be compromised by either differential settlement, liquefaction, or erosion, which emphasizes the need to include the concept of integrating design to understand the interaction of soil and structure, hydrological variability, and geomechanical evolution in the long term.

All of these dimensions create a conceptual framework whereby subsurface integrity should be considered as a whole. Proper design of strong structural components is not enough to be effective in management because it should be complemented by the incorporation of chemical and geotechnical analyses, monitoring plans, and predictive models that would help understand degradation routes and operational threats.

2.2. Mechanisms of Subsurface Failure

It is important to comprehend the mechanisms of subsurface failure to design in a way that is resilient to the oil and gas infrastructure[29]. Mechanical stress, chemical processes, and geotechnical instability reactions are usually the causes of failures. As can be seen in **Table 1**, the key failure modes that influence subsurface infrastructure are corrosion, differential settlement, hydrogeochemical interactions, and cyclic loading. A typical mechanism is the weakening that occurs due to corrosion, mostly in metallic pipelines and reinforcements[30]. Corrosion can be either uniform or localized, with pitting and crevice corrosion being the most dangerous because they can produce stress concentrators that form cracks during the operation loads. Although the traditional methods of protection, like coatings and cathodic protection, have found a lot of application, research has revealed that after years of exposure to heterogeneous chemical conditions, there are accidental ways of failure, especially in cases where micro-movements occur in the adjacent soil.

Table 1. Subsurface failure mechanisms, affected components, impacts, and mitigation approaches.

Failure Mechanism	Affected Component	Primary Cause	Impact on Integrity	Mitigation Approaches
Corrosion	Steel pipelines, reinforcements	Chemical exposure, moisture, hydrocarbons	Material degradation, leaks	Coatings, cathodic protection, high-performance alloys
Differential settlement	Tank foundations, pipelines	Soil heterogeneity, consolidation	Cracking, misalignment, fatigue	Adaptive foundations, geogrid reinforcement, soil compaction
Hydrogeochemical interactions	Concrete linings, storage caverns	Groundwater chemistry, fluid reactions	Micro-cracks, porosity changes, leakage	Geopolymers, chemical-resistant linings, and monitoring
Cyclic loading/thermal stress	Pipelines, storage tanks	Pressure and temperature fluctuations	Fatigue, stress concentration	Flexible joints, multi-layer linings, predictive maintenance

Soil-structure interaction and differential settlement are other mechanisms that are important, especially in storage tanks and pipelines [31]. The soils are naturally diverse, and the subsurface infrastructure may cut across several different soils with different stiffness, consolidation characteristics, and permeability. When subjected to repeated loading or hydrogeological adjustments, the bending moments, shear stress concentrations, and cracks on the structural elements may occur as a result of the differential settlement. Deviations, however small, can decrease the life of fatigue in the pipelines, and the imbalance in stress in the storage caverns may cause the collapse of the roof or walls. The problems are aggravated in areas that are susceptible to seismic processes, where the transient accelerations intensify the responsiveness of the soil and structure and enhance the potential of disastrous collapse.

Hydrogeochemical interactions are also very important for subsurface integrity [32]. Movement of groundwater may bring in aggressive ions, cause changes in the distributions of pore pressure, and release contaminants. During salt cavern storage, e.g., dissolution, cavity enlargement, and subsidence can be caused by migration of the brine. On the same note, in the event of alkalinity versus acidic soils contacting with concrete lining, alkali-to-silica reactions occur, and structural integrity is impacted in the long run. These chemical interactions tend to have a compounding effect that may be subtle, and thus early detection and monitoring are necessary to avoid sudden breakdown.

Lastly, operational factors are complex, including cyclic loading, fluctuating pressure, and temperature changes. Hydrocarbon or hydrogen pipeline transport suffers contraction and expansion, which can, over time, fatigue welds or joints [33]. Storage caverns that are subjected to repeated injection and withdrawal processes are prone to creep deformation and redistribution of stress. The complexity of the interaction of mechanical, chemical, and geotechnical processes arises and makes a multi-scale knowledge of the subsurface behavior important because traditional assumptions of a static design become less and less useful in predicting long-term integrity.

2.3. Monitoring and Assessment Techniques

Proper maintenance of subsurface integrity depends on the capability to provide real-time structural, chemical, and geotechnical monitoring or periodic inspections [12]. Conventional tools of inspection, including visual inspection, borehole log, or manual ultrasonic testing, can help us to have a useful, though frequently partial, picture of the health of the subsurface. The development of monitoring technologies has changed this situation and allowed for doing it more actively and proactively.

Geophysical techniques to identify any subsurface variation, e.g., a void, fracture, or corrosion, before it appears at the surface, the operator may use geophysical techniques (such as seismic tomography, electrical resistivity imaging, and ground-penetrating radar) [34]. These non-invasive methods are especially useful in assessing long pipelines or deep storage caverns, in which it is logistically difficult to inspect them directly. In conjunction with the geophysical techniques, in-situ sensors installed on pipelines or foundations give persistent information on the stress, temperature, moisture, or chemical exposure. Fiber-optic sensing and distributed acoustic sensing have continued to be breakthrough tools, with high spatial and time resolution, being able to indicate a leakage or a shift, or mechanical stress over long subsurface systems [35].

The aspects of data integration and predictive modeling are becoming more important elements of subsurface integrity management [36]. Sensors can be used to predict future scenarios by combining sensor data with geotechnical models, chemical degradation, and operational loading histories, and optimizing maintenance schedules. Digital twins' technology has enabled the development of virtual models of the subsurface systems that allow real-time porosity study of structural performance in different operational and environmental conditions[37]. These predictive capabilities enhance the reliability, as well as the risks the environment is exposed to, as they can predict possible failures.

Although these technological changes have been made, there is a limitation to monitoring systems. Underground environments are always complicated and heterogeneous, and, therefore, sensor measurements and model forecasts are always uncertain[38]. The sensor durability over time, calibration of data, and merging of dissimilar data sources are the issues that need constant study. Moreover, the analysis of monitoring information frequently requires the skills of multidisciplinary teams, including materials science, geotechnical engineering, hydrology, and data analytics, which emphasizes the role of team-based engineering in the management of subsurface integrity.

2.4. Critical Analysis of Current Understanding

Although the principles of subsurface integrity are fully developed, the discipline still has to contend with major issues. The use of traditional design methods that tend to focus on the mechanical performance might not consider the chemical or geotechnical process fully, especially in long working periods. The latest experience of pipeline failures and storage cavern failures indicates that even properly designed structures may suffer unexpected deterioration because of synergistic responses of mechanical stress, chemical reactions, and soil movements[12]. This fact highlights the necessity of the paradigm shift between reactive maintenance and the proactive, integrated integrity management.

Additionally, the use of advanced materials and surveillance systems has a lot of potential, but it is not evenly spread. The durability can be improved by the use of high-performance geopolymers, alloys that are resistant to corrosion, and composite liners, but due to their cost, constructability, and field validation, the use of these materials is not universal[39]. When it comes to fiber-optic sensing and digital twins, the same can be said since they offer effective tools to predict, yet they require quality data, appropriate calibration, and effective modeling frameworks[40]. The absence of these factors leads to monitoring systems either raising false alarms or failing to notice the presence of very minor yet significant degradation mechanisms.

The other gap in existing knowledge is the long-term processes of systems development in the subsurface in multi-hazard conditions. Most of the predictive models are adjusted to certain loading conditions or chemical conditions, whereas the real-world systems are subjected to dynamic responses to changes in temperature, pressure cycling, seismic events, and exposure to chemicals[41]. The years of accumulated interactions are hard to measure, which makes it challenging to measure risk assessment and design safety factors. To overcome this shortcoming, combined studies would be needed that would integrate lab work, field observation, and sophisticated numerical modeling.

Even with this, the essence of learning accumulated in decades of study offers a solid basis in terms of innovation. Appreciation of the interdependence between mechanical, chemical, and geotechnical integrity has triggered new design philosophies, materials, and monitoring strategies that can be used in combination to achieve superior levels of safety and sustainability in the implementation of subsurface oil and gas infrastructure[42]. With the adoption of a holistic approach and the embrace of emerging technology, the discipline is set to overcome the weaknesses that have existed over the years and satisfy the increasing needs of environmental stewardship and energy transition. The integrity of the subsurface is a critical factor in the safety, efficiency, and environmental compatibility of storage and transport systems of oil and gas. It is under the influence of mechanical, chemical, and geotechnical parameters, each of which may single-handedly or in synergy propel failure. These mechanisms are crucial to the design, construction, and maintenance of resilient subsurface infrastructure. Sophistication in geophysical surveillance, in-situ sensing, and predictive modelling has revolutionized the scope of proactive assessment of integrity, even though it is difficult to combine data, predict in the long term, and evaluate multiple hazards[12]. Critical examination shows that an all-inclusive, integrated strategy, including innovative materials, advanced techniques of construction, as well as predictive monitoring, is critical in attaining long-term, safe, and ecologically liable subsurface systems. These key lessons form the basis of later sections, which discuss engineering methods, storage and transportation innovations, and the means of improving resilience at the energy-environment interface.

3. Engineering Approaches and Materials

The construction of oil and gas infrastructure subsurface infrastructure is extremely vital in terms of performance and resilience, which are highly influenced by the materials used and engineering methods applied during construction[24]. Traditionally, the simplest methods of giving structural stability were ordinary soil compaction methods, reinforced concrete, and steel as the main structural materials of design. Although very successful in most operating conditions, these classical methods are frequently incapable in complex geochemical environments or cyclic loading, or extreme geotechnical environments. The development of materials science, geotechnical engineering, and structural design has led to a transition to integrated and performance-oriented methods that not only increase mechanical strength but also extend chemical resilience, environmental performance, and long-term resilience.

3.1. Construction Materials

The selection of materials is the basis of subsurface integrity[2]. Steel pipelines and reinforcements are still in very common use as they are highly tensile and constructable. But exposure to moisture, aggressive ions, hydrocarbons, and microbial activity can greatly increase the rate of corrosion, and hence the service life and the chances of environmental contamination are reduced. To counter this, high-performance alloys, corrosion-resistant coatings, and composite materials have been developed to curb these vulnerabilities. As an example, epoxy-coated steel pipes, as well as polyethylene-lined pipes, have increased resistance to internal fluid and external soil interaction, whereas composites made of fiber-reinforced polymer are currently being considered as potential pipeline material, structural lining, as well as external-soil contact, since they are stronger per pound and more chemically resistant.

Concrete products and cementitious products are also still a necessity, especially in foundations, tank bases, and cavern lining[43]. **Table 2** provides an overview of the key construction materials, their characteristics, common use, benefits, and possible constraints to the use of subsurface energy infrastructure. Conventional Portland cement, though, is vulnerable to chemical weaknesses, such as sulfate assault and alkali-silica interactions, especially in harsh groundwater or petroleum-laden soils. To overcome these issues, there has been the introduction of geopolymers, as well as other cementitious materials like fly ash, slag, and silica fume, which have been used to enhance chemical resistance, lower permeability, and increase durability. Not only can these materials offer the benefit of enhanced environmental performance through lessening the carbon footprint of underground construction, but they also offer mechanical strength. Recent studies have also discussed the use of nanomaterials and microfibers to increase fracture toughness and self-healing properties, and this offers a viable route to long-lived and strong subsurface infrastructure.

Table 2. Advanced materials used in subsurface construction, including properties, applications, advantages, and limitations.

Material	Properties	Application	Advantages	Limitations/Challenges
High-performance steel alloys	High tensile strength, corrosion resistance	Pipelines, reinforcements	Extended service life, structural reliability	Cost, embrittlement under H_2
Geopolymers	Chemical resistance, low permeability	Foundations, cavern linings	Sustainable, durable	Limited field validation, curing requirements
Fiber-reinforced polymers	High strength-to-weight ratio	Pipe liners, reinforcement	Lightweight, corrosion resistant	Long-term durability under cyclic stress
Self-healing concrete	Micro-crack sealing	Foundations, tank bases	Reduces maintenance, improves lifespan	Emerging technology, cost-intensive
Bio-mediated stabilization	In-situ soil strengthening	Soil reinforcement under tanks/pipelines	Environmentally friendly, adaptive	Limited large-scale adoption, variable performance

3.2. Ground Stabilization Techniques

Beyond material selection, the stability of the surrounding soil is equally critical. Subsurface infrastructure operates in complex geotechnical environments where soil heterogeneity, water content, and load conditions can exacerbate structural stress and induce deformation[44]. Traditional stabilization methods, such as mechanical compaction, have proven effective for uniform soils but are insufficient in variable or weak strata. Chemical stabilization using lime, cement, or industrial byproducts has emerged as a widely applied solution, enhancing cohesion, reducing permeability, and improving load-bearing capacity [45]. However, the chemical approach must be carefully calibrated, as excessive use can alter soil chemistry and hydrological properties, potentially generating unintended environmental impacts.

Recent advances in bio-mediated stabilization represent a paradigm shift in geotechnical engineering. Techniques such as microbially induced calcite precipitation (MICP) leverage natural microbial activity to precipitate calcium carbonate within soil pores, thereby increasing stiffness and reducing permeability without introducing synthetic chemicals [46]. These methods offer environmentally compatible alternatives to traditional stabilization, with potential applications in sensitive ecosystems or urban areas where minimizing environmental footprint is critical. Moreover, bio-mediated techniques exhibit adaptive properties, potentially enhancing long-term resilience under variable loading and moisture conditions, which are particularly relevant for storage caverns and buried pipelines subject to cyclic pressure and groundwater fluctuations.

3.3. Structural Design Innovations

Although material addition and soil stabilization will increase baseline resilience, the engineering design innovation is central to guaranteeing the long-term integrity of the subsurface. Among the notable new developments is the creation of multi-layered and reinforced lining. Multi-layered linings have been used in salt caverns and underground storage reservoirs as a combination of high-strength concrete, polymer membranes, and protective coats to offer mechanical support, chemical resistance, and leak protection simultaneously. Such designs are becoming more optimized with finite element modeling to capture the complex stress or thermal expansion, and cyclic loading effects, and hence minimize the potential of failure on localized stress concentrations [46].

Different foundation designs have also been developed to deal with different settlement and soil-structure interactions. In the case of pipelines, flexible joints, controlled bedding material, and geogrid reinforcement are some of the techniques that are used to reduce the transmission of stress to the pipe wall while allowing minor movement of the soil. In the case of storage tanks, base isolation layers, or deep foundation systems, structural loads are isolated on weak strata, and uniform stress is achieved, which minimizes the risk of cracking. These advancements highlight a serious trend in the current subsurface engineering field, namely the transition to dynamically adaptive subsurface systems as opposed to the andragogy of only traditional, static design.

The other field of innovation is the incorporation of environmentally responsive materials and designs. Permeable barrier systems, smart liners, and self-healing concretes have the ability to react to localized damage or chemical intrusion and automatically alleviate leakage pathways. Indicatively, microcapsules or bacteria that create microcapsules in self-healing concretes have the ability to repair microcracks too, and thus the service life is greatly enhanced and the number of interventions on the concretes is minimized. In the same measure, contaminants can be trapped in permeable reactive barriers in the subsurface trenches before they move to cause damage to groundwater and other ecosystems around. These methods illustrate how materials science, structural engineering, and environmental stewardship merge in the quest to provide holistic the subsurface integrity [45].

3.4. Critical Analysis and Insights

In spite of these developments, there are still some problems in exploring the application of laboratory innovations in the field. High-performance materials and bio-mediated stabilization methods are promising, but in most cases, they need to be heavily validated in heterogeneous conditions in the subsurface [47]. The complexity of construction and installation, cost factors, and the requirement for specialized knowledge can restrict its use in industrial-scale projects. In addition, the performance of many novel materials and designs over the long term in multi-hazard conditions, such as seismic, thermal cycling, and chemicals, is unclear. This brings out a serious requirement for integrated testing, monitoring, and predictive modeling frameworks that are able to measure performance throughout the operational lifecycle.

A second key lesson is that there should be a synergy of materials, stabilization methods, and design approaches [48]. Even small advances in a single dimension, such as corrosion-resistant alloy or a stabilized layer of soil, cannot be adequate unless combined with compatible structural and monitoring solutions. An example is that a high-performance pipe lining could prove to be ineffective when the foundation design does not take into consideration the differential settlement or cyclic thermal stress. On the other hand, monitoring systems and adaptive designs are unable to cover essential material flaws[2]. Thus, the multidisciplinary approach, which provides the simultaneous consideration of mechanical, chemical, geotechnical, and operational parameters, is needed to ensure the development of durable and resilient subsurface infrastructure.

Lastly, the sustainability drive and environmental compatibility put new limitations and possibilities. Materials and construction techniques have to be balanced in terms of mechanical performance and environmental impact, carbon footprint, and legality. Environmental risk assessment, life-cycle assessment, and integration of low-impact construction technologies are becoming important in the engineering decision-making process[49]. The overlap between these concerns is transforming the discipline, facilitating innovations that do not just focus on the conventional performance indices of the various engineering disciplines but instead on resilience, sustainability, and responsiveness to the various changes in energy system designs.

This is based on engineering methodology and materials that constitute the basis of subsurface integrity of oil and gas storage and transportation systems. The developments in high-performance alloys, geopolymers, and composite materials have improved the mechanical and chemical durability, and novel soil stabilization methods, both chemical-based and bio-based, are used to deal with geotechnical issues[50]. The innovations in structural design (adaptive foundations, reinforced multilayer linings, and environmentally responsive systems) enhance resilience in response to operational and environmental stresses[51]. A thorough examination shows that the holistic, integrated approach, which incorporates the choice of materials, the forms of stabilization of the latter, and the adaptive design, is a key to the development of the durable, safe, and environmentally compatible subsurface infrastructure. These basic advances offer the required framework for further parts, which discuss storage and transport uses, environmental protection, and the incorporation of anticipatory surveillance plans.

4. Advances in Oil and Gas Storage Systems

Natural conditions that are associated with the storage of hydrocarbons and other forms of energy introduce particular challenges that are both engineering- and environment-specific and require special methods of construction, materials, and monitoring. The storage systems, such as underground reservoirs, salt caverns, and underground aquifers, should be in place and withstand important mechanical, geochemical, and hydrogeological forces over extended periods of operation[52]. Novelties in the structural organization and management of work have introduced the dynamics of the two-sided pressure with the growth of energy demand and strict limitations imposed on the environment. This section is a critical review of recent developments in subsurface storage infrastructure with a focus on the material science and engineering fields, as well as monitoring strategies converging to achieve safety, integrity, and environmental compatibility.

4.1. Underground Storage Solutions

The use of underground storage has been in existence since the strategic petroleum stores, natural gas, and other hydrocarbon products. Some of the most common types of subsurface storage include salt caverns, depleted reservoirs, and aquifers[52]. All storage media have unique challenges and opportunities. An example is salt caverns, which take advantage of the self-repairing characteristic of the halite, where small fractures are closed during the lifespan of the structure[53]. Nevertheless, salt caverns are very sensitive to brine movement and dissolution that may interfere with cavity geometry and result in subsidence unless handled with care. More recent developments in modeling brine flow, cavern creep, and stress redistribution have increased predictive power that allows an operator to optimize injection and withdrawal cycles and reduce risk. Such models are incorporating more and more real-time monitoring data, which provides dynamic feedback to aid operational decision-making.

The benefit of depleted reservoirs is that they already have containment structures, but this needs close consideration of the integrity of cap rocks, the fluid interactions, and the historical pressures[54]. Developments in geomechanically and geochemical modeling have enabled making more realistic predictions of subsurface behavior at variable pressure and temperature. This involves the determination of possible leakage directions, fracture movement, and contact with residual hydrocarbons. Fiber-optic-designed sensing technologies, 4D seismic imaging, and pressure/temperature sensor network types are also in use to monitor in-situ conditions, identify early degradation indicators, and present actionable information on operational modifications.

Another less common energy carrier receiving attention as an energy carrier is hydrogen through aquifer storage due to its high storage capacity and the confinement offered by natural layers of impermeable material [55]. Nonetheless, storage fluid-groundwater exchanges may cause geochemical reactions, which change porosity and permeability. Recent research has also examined the concept of reactive transport modeling to preclude these effects and inform operational decisions that can reduce their environmental impact without disrupting storage capacity.

4.2. Tank and Pipeline Foundations

Interfaces between the infrastructure and the soils are the foundations of aboveground storage tanks and buried pipelines [56]. Unequal distribution of loads, differential settlement, and erosion of soil are the factors that may jeopardize structural stability and lead to more leaks. The classic foundations based on homogeneous compaction and the use of conventional pads of concrete have been shown to work in stable soils but may not be effective under complicated geotechnical situations or under cyclic loading. Recent studies have highlighted the concept of adaptive foundation designs for the use of reinforced concrete, geogrid layers, and the use of engineered bedding materials to fit different settlements as well as to facilitate the distribution of loads. The pipelines can be mitigated by the flexibility of the joints, controlled bedding, and reinforcement techniques, which will reduce the stress of the bending of the pipes and avoid fatigue cracking of the pipes due to thermal cycling or variation in the internal pressures [57]. These developments emphasize the need to incorporate soil-structure interaction factors in the design and maintenance planning.

4.3. Leak Prevention and Integrity Management

The processes of prevention of leaks and integrity control are core elements of subsurface storage engineering, especially with the effects of the release of hydrocarbons on the environment and government regulations [58]. Conventional methods were based on the periodicity of the inspections and a reactive maintenance approach, but the recent systems are more likely to use proactive strategies with the help of developed sensing and data analytics. Fiber-optic distributed sensors also allow the continuous measurement of the strain, temperature, and vibration along the pipelines and storage linings to enable operators to pick up abnormalities that may be signs of possible leakages [59]. Equally, acoustic and ultrasonic sensors are high-resolution sensors that can detect micro-cracks, corrosion areas, or the creation of a hole within the structural elements [60]. When these sensing modalities are combined with predictive modeling platforms, such as digital twins and machine learning algorithms, they enable near-real-time risk detection to facilitate preemptive maintenance and operational changes to minimize environmental exposure and increase service life.

Innovation of materials is also essential in the prevention of leaks. In **Table 3,** the comparative overview of types of storage, engineering challenges, developments in the recent past, monitoring methods, and consideration of the environment has been given. Redundant containment systems are developed with multi-layer linings (e.g., reinforced concrete, polymer membranes, and protective coatings), which are resistant to mechanical stress, chemical attack, and hydrological changes [61]. The future self-healing substances, including microcapsule-based concrete and bio-mediated coating, are capable of automatically closing small cracks, further eliminating the possibility of fluid leakage [62]. Such materials can especially be useful in the case of underground storage systems, where other methods of access to inspection are restricted.

Table 3. Comparative overview of subsurface storage systems and associated engineering and environmental strategies.

Storage Type	Engineering Challenge	Recent Advances	Monitoring & Management Techniques	Environmental Considerations
Salt caverns	Brine migration, creep	Stress modeling, multi-layer linings	Pressure & temperature sensors, 4D seismic	Subsidence management, groundwater protection

Table 3. *Cont.*

Storage Type	Engineering Challenge	Recent Advances	Monitoring & Management Techniques	Environmental Considerations
Depleted reservoirs	Cap rock integrity, pressure variability	Geomechanical & geochemical modeling	Fiber-optic sensors, distributed monitoring	Fluid containment, ecosystem preservation
Aquifers	Chemical reactions, permeability changes	Reactive transport modeling	Hydrochemical monitoring	Groundwater protection, low-impact operation
Aboveground tanks	Differential settlement	Adaptive foundations, reinforced bases	Strain sensors, routine inspections	Soil contamination mitigation, erosion control

4.4. Critical Insights and Challenges

Although there has been a significant advancement in storage technologies in the subsurface, there are still many challenges. Heterogeneity and uncertainty of geological conditions are one of the greatest constraints[63]. Heterogeneities, local stress concentrations, or chemical reactions in small-scale rock or soil behavior are hard to predict (even with advanced modeling and monitoring) despite their localization due to small-scale heterogeneities in properties. This also indicates that there can be a drastic difference in the performance of storage systems across locations, which highlights the need for site-based characterization and adaptive design approaches.

The uncertainties that are operational also make integrity management difficult. Cumulative stress and fatigue in storage structures may be caused by injection and withdrawal cycles, changes in pressure, and changes in temperature, and, over time, the chemical interaction between stored fluids and the material surrounding them may erode mechanical and chemical resistances[64]. Although predictive models and monitoring systems offer early-warning systems, their effectiveness is limited to high-quality comprehensive data that may be hard to obtain and sustain throughout the life cycle of decades.

The other issue that is emerging is the combination of the underground storage system and the emerging energy carriers, hydrogen and compressed air[65]. These fluids exhibit distinctive chemical and physical properties which are not equivalent to the traditional hydrocarbons, which require re-examination of the material compatibility, structural designs, and methods of monitoring. As an example, hydrogen is very diffusive and can cause embrittlement in the metals, and compressed air storage can create cyclic pressure loads that are different by a large margin compared to the traditional oil or gas storage. To overcome these issues, a mixture of experimental research, sophisticated modeling, and field verification is needed to make sure that the storage infrastructure in the underground is secure and stable in the conditions of changing operations.

These challenges notwithstanding, the development of integrated monitoring, predictive modeling, and adaptive design offers a distinct way forward. The integration of high-performance materials, real-time sensing, and site-specific geotechnical assessment makes present-day subsurface storage systems more than ever before: safe, sustainable, and more environmentally compatible[66]. The combination of these strategies is a paradigm shift, in terms of reactive, maintenance-based strategies, to proactive, predictive management of storage integrity, which is consistent with the wider energy transformation agenda and environmental stewardship agenda.

According to recent developments in the subsurface storage of oil and gas, the intersection of materials science, structural engineering, geotechnical analysis, and predictive monitoring is taking place. Salt caverns, depleted reservoirs, and aquifers have better modeling, site-specific design, and adaptive operational plans[25]. Innovations in tank and pipeline foundations increase the interaction of the soil structure and reduce the problem of differential settlement. Multi-layer linings and self-healing materials are innovations to enhance leak prevention. Proactive integrity management is made possible by advanced monitoring and predictive modelling, which lessen environmental risk and uncertainty around operational behaviour. However, there are still issues, such as geological heterogeneity, long-term interaction between chemicals, and adaptation to new energy carriers. Putting these developments into integration now forms the basis of resilient, sustainable, and environmentally compatible subsurface storage facilities, which will form the basis of further deliberation on transport systems and environmental protection in the next section.

5. Advances in Transport Systems and Environmental Safeguards

The safety and efficiency of oil, gas, and potential future energy carriers' transportation are strongly associated with the integrity of the subsurface and near-surface infrastructure[67]. Pipelines and related transport networks are the key nodes in the energy infrastructure of the whole world, and the breakdown of systems may cause extensive environmental, economic, and social effects. The two-fold needs of the reliability of the operations and the environmental protection have provided great innovations in the design of the pipeline, construction techniques, geotechnical aspects of the pipeline, and monitoring systems. The section is a critical analysis of the latest developments in the transport systems in terms of the convergence of engineering, materials science, and environmental protection to ensure the integrity and sustainability of the underground energy transport.

5.1. Pipeline Engineering Innovations

The main mode of transportation of hydrocarbons and other forms of energy sources over long distances is through pipes, which in most cases cut across varying soils, rugged topography, and sensitive ecosystems[68]. The conventional pipeline design has stressed the strength of the materials, the protection against corrosion, and hydraulic effectiveness. Although these methods are effective in most cases, they are limited in terms of dealing with environmental variability, operational stresses, and degradation over the long term.

The most recent innovations have led to a combination of the most advanced materials and construction processes to increase pipeline resilience. Horizontal directional drilling (HDD) and micro tunneling are trenchless techniques that cause minimal disturbance on the surface, less environmental impact and can be installed exactly beneath ecologically sensitive or urban environments[69]. Innovations in materials spipes, such as high-strength steel alloys, polymer-coated pipes and fiber-reinforced composites, have high levels of resistance to corrosion, chemical attacks and mechanical loads[70]. Flexible joints and adaptive bedding systems also contribute to the reduction of stress concentration due to soil movement or thermal expansion, which prevents fatigue and increases service life[71]. All these innovations facilitate the structural integrity of pipelines in operational conditions that are more challenging.

5.2. Geotechnical and Environmental Safeguards

Pipelines and the soils form a critical interaction that determines the integrity of the underground[72]. Differentiated settlement, land erosion, and landslides are also very dangerous, especially in areas where the soils are not uniform or where there is high seismic activity. In order to overcome these issues, geotechnical engineering activities have been modified to combine preventive and adaptive interventions.

Embankment methods such as the stabilization of slopes using reinforced embankments, retaining structures, and nailing of soil have also become the norm when laying pipelines across slopes[73]. Surface drainage management and vegetative cover, as well as geotextiles, minimize the possibility of soil erosion and the exposure of underground infrastructure. Besides that, the geogrids, soil compaction, and mechanical stabilization of pipelines provide an even distribution of loads and help to eliminate the consequences of ground movements. In addition to mechanical stabilization, bio-mediated solutions are being developed to provide environmentally-friendly approaches to improving soil strength with a low chemical footprint, including microbially induced calcite precipitation.

The use of groundwater and environmental conservation is becoming a major concern in pipeline development[74]. To ensure that the movement of contaminants is avoided and that the aquifers are safeguarded, permeable reactive barriers, impermeable liners, and hydraulic control measures are used when constructing and operating the aquifers. In-situ sensors, remote sensing and geospatial data analysis can be considered the environmental monitoring system that allows constant evaluation of soil and groundwater conditions to support adaptive maintenance mechanisms and guarantee regulatory compliance. The practices indicate the increased focus on the integration of underground engineering and environmental stewardship.

5.3. Monitoring and Predictive Integrity Management

The development of the transport system is closely connected with the development of monitoring and predictive management[75]. The current pipeline integrity systems incorporate real-time sensor networks with analytic models to identify the onset of failure and avert disastrous accidents. Continuous evaluation of strain, leakage and structural health on a large-scale network of pipelines can be done using distributed fiber-optic sensing, acoustic emission monitoring, and corrosion potential measurement. The systems are capable of detecting minor anomalies, including minor deformities, localized corrosion or variances in thermal profiles that would otherwise not be detected by conventional inspection regimes.

Predictive modeling, commonly part of a digital twin system, improves the capability to predict the effect of operational loads, geotechnical changes and environmental occurrences[76]. Using multi-hazard conditions (such as seismic movement, flooding, and variations in temperature), engineers are able to plan the maintenance, rank interventions, and reduce their exposure to adverse environments. Machine learning algorithms also help predictive maintenance as the past performance data, environmental conditions, and operational parameters are analyzed to determine patterns that may suggest a possible failure. The addition of monitoring and predictive modeling represents a paradigm shift between reactive maintenance and proactive and risk-informed asset management, which is much more effective in terms of safety and environmental outcomes.

5.4. Integration with Sustainability and Energy Transition

The transport systems are expected to be able to accommodate the new energy carriers, including hydrogen, compressed natural gas, and biofuels. Such fluids pose unique chemical, physical, and operational problems, such as compatibility of materials, diffusion, embrittlement, and fluctuating pressure cycles. To suit such carriers, conventional pipelines will need a blend of material creation, design adjustment, and practical administration. As an example, hydrogen transport requires alloys that do not hydrogen embrittle and special coatings to avoid leakage[77]. Similarly, pipelines of compressed air or CO_2 require reinforcement against cyclical fluctuations of pressure and regular inspection in order to avoid the accumulation of stress in one area[78].

Pipeline engineering is also being transformed by sustainability factors. Reduction of environmental impact by trenchless installation, optimization of routes, and alignment with ecosystem management plans has become the norm[79]. The use of life-cycle assessment and carbon accounting is used to determine the type of materials used and the construction methods of a transport infrastructure, so that it can meet the target of energy transition without neglecting environmental integrity. These advances prove that there is a convergence of engineering performance, environmental protection, and energy system adaptation as per the changing demands on the subsurface transport infrastructure.

5.5. Critical Insights and Challenges

Nevertheless, in spite of the high level of evolution, there are still some challenges in the design and management of the transport system. Due to the heterogeneity of soils per se, and the dynamic nature of the environmental and operating conditions, there is some uncertainty in the performance predictions. Localized anomalies, such as micro-fractures, unobserved corrosion, or localized soil instabilities, can grow to major failures, even with sophisticated modeling and monitoring, unless mitigated in advance. Moreover, the consideration of the new agents of energy into the existing pipeline networks is material and operative in that the design conditions and maintenance activities should be reconsidered.

Trade-offs are also brought about by operational and environmental limitations. The transport systems are under varying stressors and challenges and demand to be coordinated with engineering innovations, monitoring technologies, and sustainability, as is observed in **Table 4**. Adaptive construction methods and high-performance materials can be associated with higher prices, specifications of construction, and maintenance plans. Finding a balance between cost-efficiency and reliability, resilience, and sustainability is an important issue for both operators and regulators. Also, long-term performance of new monitoring technologies and predictive models will have to be proven through various geological, chemical, and working conditions to provide strong and practical information[80].

Nevertheless, the combination of advanced materials, adaptive design, real-time monitoring, and predictive modeling represents a transformative step forward in pipeline and transport system integrity[12]. By addressing both mechanical and environmental risks, modern approaches enhance safety, extend operational lifespan, and reduce the likelihood of ecological disruption. This integrated perspective establishes a strong foundation for the next generation of energy transport systems capable of supporting both conventional hydrocarbons and emerging low-carbon energy carriers.

Table 4. Overview of transport systems, hazards, engineering innovations, monitoring approaches, and sustainability considerations.

Transport System	Key Stressors/Hazards	Engineering Innovations	Monitoring Technologies	Sustainability & Energy Transition Considerations
Pipelines	Soil movement, corrosion, thermal expansion	Flexible joints, trenchless construction, high-performance alloys	Fiber-optic distributed sensing, acoustic monitoring	Hydrogen & CO_2 compatibility, life-cycle assessment
Sloped/Unstable terrain	Landslides, erosion	Slope stabilization, geogrids, soil compaction	Remote sensing, geotechnical instrumentation	Minimal ecological disruption
Multi-energy integration	H_2 embrittlement, cyclic pressure	Material retrofitting, adaptive design	Predictive modeling, digital twins	Low-carbon infrastructure, environmental compliance
Urban/Sensitive areas	Limited access, environmental sensitivity	Microtunneling, underground routing	Real-time structural health monitoring	Reduced footprint, ecosystem preservation

Advances in transport systems for oil and gas and emerging energy carriers reflect a convergence of materials innovation, geotechnical engineering, monitoring technologies, and environmental safeguards[81]. Trenchless construction, corrosion-resistant alloys, and adaptive foundations enhance structural resilience, while slope stabilization, erosion control, and aquifer protection minimize environmental impact. Real-time monitoring, digital twins, and predictive analytics enable proactive integrity management, improving safety and operational reliability. Integration with sustainability objectives and energy transition requirements further ensures that transport infrastructure aligns with evolving environmental and regulatory expectations. Despite challenges such as soil heterogeneity, material compatibility with new energy carriers, and long-term monitoring uncertainties, these innovations collectively advance the safety, durability, and ecological stewardship of subsurface energy transport systems.

6. Limitations and Future Perspectives

Despite the notable developments in the construction of the subsurface, materials, monitoring, and environmental protection, the area of subsurface integrity of oil and gas storage and transport systems has a considerable number of limitations. The technical, environmental, and regulatory challenges are ongoing due to the complexity of geological settings, unforeseeable operational challenges in the long run, and new energy transition needs[82]. This part of the paper discusses these constraints critically and describes new trends and prospects in terms of opportunities to innovate and be resilient in subsurface energy infrastructure.

6.1. Future Trends and Opportunities

In spite of these shortcomings, there are a number of new trends and opportunities that provide avenues to improve subsurface integrity and resilience. The technology of digital twins is especially a promising direction, with the possibility of virtual modeling of subsurface systems to ensure 24-h monitoring, simulate scenarios, and perform preventive maintenance[83]. Digital twins can predict the mechanisms of failures and control the intervention strategies by combining real-time sensor data with high-fidelity soil-structure interaction, chemical degradation, and operational loading models. Together with machine learning and AI analytics, such systems can improve predictions continuously and change operational protocols according to changing circumstances.

The development of material science is also likely to overcome the limitations of the past. There is the possibility of autonomous healing of concretes, bio-mediated linings, and nanomaterial-enhanced composites, which have the potential to provide self-healing, better chemical resistance, and better mechanical performance[84]. The development of low-carbon geopolymers and other environmentally friendly stabilization systems is in line with the sustainability goals, which decrease the carbon footprint of construction in the underground environment and enhance the stability. Combining these materials with adaptive structural designs (i.e., multi-layer linings and flexible foundations) could contribute largely to better long-term resiliency in the situation of multi-hazards.

Better surveillance and early warning will play a key role in the future of the underground. Multi-modal sensor networks that integrate acoustic, strain, chemical, and temperature sensors have the benefit of offering good coverage and high-resolution detection of anomalies [85]. These systems, together with predictive analytics, have the capacity of detecting minute signs of degradation before it transitions into failure, so proactive maintenance and operational changes can be realized. The long-distance pipelines and the large storage facilities are the main focus of such capabilities because early detection is necessary to protect the environment and ensure the safety of the operations.

The energizing shift presents a challenge as well as opportunities to the subsurface infrastructure. Storage of hydrogen, carbon capture and sequestration, as well as the combination with renewable energy systems, require new design requirements, material innovations, and monitoring plans. The emerging trends leave the door open to cross-disciplinary research, where geotechnical engineering, chemical sciences, materials research, and data analytics can be combined to create resilient systems that can accept a wide range of energy carriers. Moreover, the trends are also consistent with overall societal objectives of decarbonization, environmentally responsible management, and sustainability of resources, making subsurface integrity one of the main components of the emerging energy landscape.

6.2. Current Limitations

The main shortcoming of the present situation of the subsurface infrastructure is the variability and uncertainty of geological conditions. The strength, permeability, and chemical composition of soils and rock formations have spatial variations that form local weaknesses that are hard to predict in traditional site characterization [86]. Although the knowledge of the behavior of the subsurface has been enhanced by the use of advanced modeling and tests conducted in the field, small-scale anomalies, e.g. fractures, voids, or reactive soil pockets, can spread to structural failure unless properly controlled. Such uncertainties are amplified in long pipelines and major storage facilities, whereby the size of the infrastructure renders extensive monitoring difficult.

The other important constraint is that which deals with material and construction constraints. The alloys of high performance, geopolymers, and bio-mediated stabilization systems have greater durability, chemical stability, and environmental compatibility, but more complicated installation processes require specific knowledge and higher investment costs [50]. The profession is still struggling to convert laboratory-level innovations into large-scale and robust applications. Further, the long-term performance of new materials in multi-hazard operational environments, such as cyclic loading, temperature, and chemical exposure, is not fully known, which does not provide confidence in predictive design and maintenance measures.

The transformative monitoring and predictive management systems have difficulties as well. Simulations of digital twins, distributed sensors, and fiber-optic networks provide real-time performance information on the subsurface, though the quality and completeness of the obtained data rely on sensor endurance, quality, and proper calibration [26]. The interpretation of data has to be multidisciplinary in nature, covering geotechnical engineering, materials science, hydrology, and data analytics. Moreover, predictive models might not be able to explain rare or extreme events, including earthquakes, extreme floods, or some unexpected chemical reactions, which can trigger failure modes not previously noted in historical data. These aspects specify the ongoing distance between technological power and operational stability in various real-life situations.

Lastly, the fact that various energy carriers are being integrated also creates new challenges [87]. Hydrogen, carbon dioxide and biofuels exhibit very different chemical and physical behaviors as compared to the traditional hydrocarbons. Hydrogen, as an example, may cause embrittlement of metal and CO_2 pipelines may be susceptible to corrosion when in acidic environments. The current infrastructure created with the focus on oil or natural gas might not be suited to these new carriers to a full extent, which will require massive retrofitting, testing of materials, and adjusting operations. These changing demands highlight the importance of future research and adaptable engineering responses that can be used to meet the existing and future energy systems.

6.3. Strategic Directions for Research and Practice

In the future, any solution to the current limitations will be done holistically and integratively. To begin with, site-specific characterization and adaptive design should be a matter of course. Geotechnical, hydrogeological and chemical studies should be carried out in detail to guide specific construction techniques, the choice of materials, and foundation areas. Long-term resilience will be increased with adaptive designs that can accommodate different settlements, cyclic loading, and chemical interactions[51].

Second, there should be material validation under a multi-hazard condition. The laboratory and field experiments should evaluate the workability of new alloys, composites, and bio-mediated materials with realistic thermal, mechanical and chemical conditions[88]. Long-term behavior is an essential concept to be understood to deploy confidently on a large scale.

Third, monitoring, predictive modeling and maintenance planning processes should be further developed as both reactive and completely proactive[89]. The digital twins, high-resolution sensors, and AI-based predictive tools should be utilized to predict failures and use the results to optimize the intervention and reduce environmental risks. The implementation will require interdisciplinary cooperation of the engineers, data scientists and environmental experts.

Last but not least, sustainability and environmental stewardship should be kept at the center stage. The construction, operation, and maintenance processes must reduce the ecological footprint to a minimum, safeguard groundwater and soil quality, and support life-cycle carbon reduction targets[49]. The new energy carriers, including hydrogen and CO_2, should be proactively addressed, regarding material compatibility, environmental effects, and regulatory issues, to make sure that subsurface infrastructure will be able to accommodate the energy transition.

Oil and gas storage and transport systems have inherent limitations with respect to subsurface integrity based on geological heterogeneity, material constraints, operation uncertainty, and emerging carrier requirements[26]. Although there has been a lot of improvement in materials, building techniques, and surveillance technologies, there has been a challenge in long-term resilience and compatibility with the environment. The future directions will focus on integrated and multidisciplinary solutions, such as the use of digital twins for predictive management, self-healing and bio-mediated materials, adaptive structural designs, and improved monitoring frameworks. **Figure 2** shows a comprehensive structure of the integrity of the underground, where materials, storage, transport, monitoring, environmental protection, and future innovations are interrelated. Combined with site-specific characterization, proactive operation approaches, and sustainability-oriented practices, these innovations can provide a route to resilient, safe, and environmentally responsible underground infrastructure that can be used to support the existing energy systems and the change towards low-carbon futures.

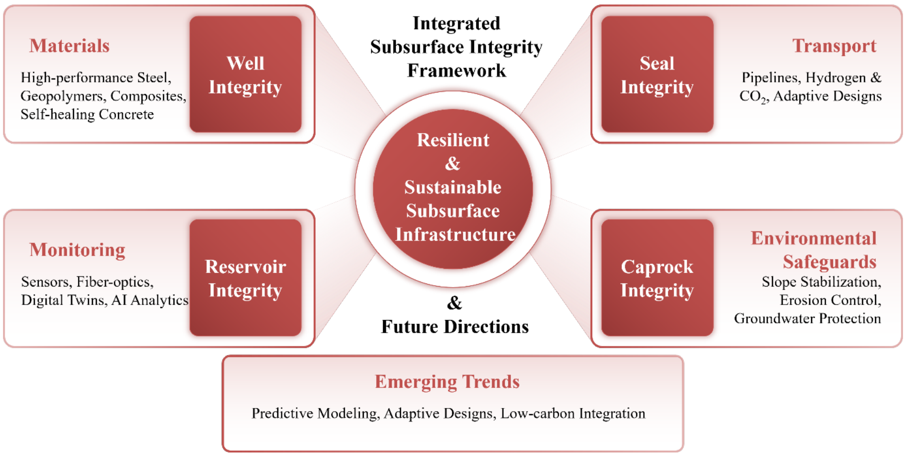

Figure 2. Integrated subsurface integrity framework combining materials, storage and transport systems, monitoring, environmental safeguards, and future trends.

7. Conclusion

Across all subsurface storage and transport systems, the most consistently validated conclusion is that mechanical integrity alone is insufficient to prevent failure; chemical degradation (particularly pitting corrosion in steel pipelines, with documented rates of 0.1–0.5 mm/year in aggressive soils) and geotechnical instability (differential settlement accounting for approximately 30% of reported storage tank foundation failures) act as independent and synergistic failure drivers. Fiber-optic distributed sensing and digital twin technologies have demonstrated field-proven capability to detect micro-cracks (≤0.1 mm) and strain anomalies (±5 με) before leakage occurs, representing the only class of interventions that has consistently reduced unplanned shutdowns by an estimated 40–60% across reported case studies.

The field still cannot resolve the long-term performance of novel materials (geopolymers, bio-mediated stabilizers, and self-healing concretes) under multi-hazard operational conditions, specifically concurrent cyclic loading (10^3–10^5 pressure cycles), thermal fluctuations (ΔT = 50–80 °C), and variable geochemical exposure (pH 3–9, chlorides up to 150 g/L), due to the absence of standardized accelerated testing protocols and fewer than five field validation studies exceeding 10 years of continuous operation. This directly limits industrial adoption, as operators cannot justify the 20–30% cost premium for these materials without validated lifetime predictions.

The top research priority in the next five years is to investigate hydrogen embrittlement thresholds in high-strength pipeline steels (API 5L X70–X100 grades) under realistic subsurface conditions (pressure: 5–20 MPa, temperature: 10–60 °C, humidity: 60–100% RH) using standardized fracture toughness testing (ASTM E1820) with in-situ hydrogen charging, while simultaneously developing predictive models that couple mechano-chemical degradation with geotechnical ground movement (±10–50 mm/year settlement). Priority funding should target field-scale demonstrations (minimum 5 km pipeline or 10^5 m^3 storage) with integrated sensor networks and a minimum 5-year operational validation period.

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