Chem Rev Lett 9 (2026) 453-465

Review Article

Chemical Review and Letters
journal homepage: www.chemrevlett.com
ISSN (online): 2645-4947 (print) 2676-7279

Chemical modulation of solid–liquid interfacial films: New insights into formation, stability, and performance

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ARTICLE INFO

Article history:
Received 05 February 2026
Received in revised form 15 April 2026
Accepted 16 April 2026

Keywords:
Solid–liquid interface
Surface functionalization
Self-assembly
Chemical adsorption
Interfacial stability
Stimuli-responsive systems

ABSTRACT

The solid–liquid interface plays a crucial role in determining the physicochemical behavior of both natural and engineered systems, influencing processes such as lubrication, corrosion resistance, catalysis, energy storage, and biomedical interactions. Interfacial films are formed through complex molecular interactions governed by surface chemistry and environmental conditions, thereby controlling macroscopic performance. Recent advances in chemical modulation strategies have enabled precise control over the structure and functionality of these films through approaches such as surface functionalization, molecular adsorption, and development of stimuli-responsive systems. This review presents a comprehensive overview of the mechanisms underlying interfacial film formation, including adsorption, self-assembly, and film growth dynamics, along with the key thermodynamic and kinetic considerations. Emphasis is placed on both covalent and non-covalent modification strategies, including pH-, ionic strength-, and redox-responsive systems, which provide tunable and adaptive interfacial behaviors. The stability of the interfacial films was critically examined in terms of mechanical integrity, chemical resistance, and long-term durability under varying environmental conditions. Advanced characterization techniques and computational modelling approaches are discussed for their ability to provide molecular-level insights into the structure–property relationships. Furthermore, the functional implications of chemically modulated interfacial films have been explored across a wide range of applications, including tribology, corrosion protection, electrochemical systems, biomedical devices, and industrial processes. Finally, emerging trends, current challenges, and future research directions are highlighted, focusing on the development of adaptive, durable, and high-performance interfacial systems.

1. Introduction

The interface between the solid and liquid phases plays a fundamental role in determining the physicochemical behavior of a wide range of natural and engineered systems. Processes such as lubrication, corrosion resistance, catalysis, energy storage, and biomedical interactions are strongly influenced by the

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https://doi.org/10.22034/crl.2026.578642.1801

phenomena occurring at this interface. A key feature governing these processes is the formation of thin interfacial films or sol–gel-like structures that develop between a solid substrate and the surrounding liquid. Although these films are typically only a few molecular layers to several nanometers in thickness, they exert a disproportionately large influence on the macroscopic properties. Consequently, understanding and controlling solid–liquid interfacial films has become a central objective in surface and interface science, materials chemistry and engineering [1].

At the molecular scale, the solid–liquid interface exhibits characteristics that differ significantly from those of bulk solids and liquids. Surface atoms possess unsatisfied coordination environments and altered bonding configurations, leading to distinct structural and energetic properties. Simultaneously, liquid molecules in proximity to a solid surface experience restricted mobility and modified solvation structures compared to those in bulk liquid. These deviations from bulk behavior create a unique interfacial environment that promotes the formation of organized molecular assemblies [2]. Interfacial films emerge through processes such as adsorption, self-assembly, and interfacial chemical reactions, which are driven by the minimization of interfacial free energy and establishment of favorable molecular interactions.

These interfacial films function as dynamic intermediaries that regulate mass transport, energy dissipation, and chemical reactivity at the interface. By controlling the exchange of molecules and ions between phases, they influence the reaction kinetics, transport phenomena, and overall system efficiency. Importantly, the structure and properties of interfacial films are not static; rather, they continuously evolve in response to variations in operating conditions and environmental stimuli, such as temperature, pH, ionic strength, and mechanical forces [3]. This dynamic behavior underscores the importance of understanding both the formation mechanisms and adaptive nature of interfacial films.

Historically, investigations of solid–liquid interfaces have relied on empirical and continuum-based models rooted in classical thermodynamics. These approaches provide valuable macroscopic insights into interfacial energy, wetting behavior, and adsorption phenomena. However, they offer a limited understanding of the molecular processes governing film formation, structural organization, and stability. In recent years, significant progress has been achieved through the development of advanced experimental techniques with high surface sensitivity and computational methods, such as molecular dynamics simulations and theoretical modelling frameworks. These tools have enabled the direct observation and analysis of interfacial structures at nanometer and sub-nanometer scales, providing deeper insights into molecular interactions and dynamic processes [4]. Consequently, interfacial films are now widely recognized as structurally heterogeneous, dynamically evolving, and highly sensitive to subtle changes in the chemical environment.

In this context, chemical modulation has emerged as a powerful and versatile strategy for tailoring the properties of solid–liquid interfacial films. Chemical modulation involves the deliberate alteration of the surface chemistry to control the intermolecular interactions, film architecture, and functional performance [5]. This can be achieved through various approaches, including the modification of surface functional groups, adjustment of molecular architecture and charge distribution, and incorporation of reactive or responsive chemical moieties. Such modifications enable the precise tuning of interfacial properties, allowing the design of films with specific structural characteristics and targeted functionalities [6].

One of the most significant advantages of chemically modulated interfacial films is their ability to exhibit adaptive and stimuli-responsive behavior. Unlike conventional static coatings, these films can dynamically respond to changes in their surrounding environment. External stimuli, such as variations in pH, ionic strength, redox potential, temperature, and mechanical stress, can induce changes in the molecular conformation, charge distribution, and intermolecular interactions within the film. This responsiveness allows the films to reorganize, self-heal, and switch between different functional states in real time, thereby maintaining optimal performance under fluctuating conditions [7]. Such adaptive behavior is particularly valuable in applications in which environmental conditions are complex or unpredictable.

The ability to engineer responsive and multifunctional interfacial films has opened new avenues for the development of advanced materials and technologies. Chemically modulated interfaces are increasingly being explored in next-generation systems that require high performance, durability, and adaptability. These include applications in tribology, where interfacial films reduce friction and wear; corrosion protection, where they act as barriers against aggressive environments; electrochemical systems, where they regulate charge transfer and ion transport; and biomedical devices, where they influence biocompatibility and surface interactions [8]. The integration of chemical modulation strategies into these applications offers significant potential for enhancing their efficiency, reliability, and functionality.

Despite these advancements, several challenges remain in the rational design and practical implementation of chemically modulated interfacial films. The formation and stability of these films are governed by a complex interplay of thermodynamic and kinetic factors and environmental influences. This complexity makes it difficult to establish clear and

predictive relationships between the molecular structure, interfacial properties, and macroscopic performance. Furthermore, the multiscale nature of interfacial phenomena, ranging from atomic-level interactions to macroscopic behavior, adds an additional layer of difficulty in understanding and controlling these systems [9].

Another critical challenge is the long-term stability and durability of the interfacial films under real-world conditions. Factors such as aging, chemical degradation, mechanical stress, and environmental fluctuations can lead to a gradual loss of functionality over time. Ensuring that chemically modulated films maintain their structural integrity and performance during prolonged operation is essential for their successful application in practical systems. Addressing these challenges requires a comprehensive understanding of the degradation mechanisms and the development of robust design strategies that balance stability and responsiveness [10].

Overall, the study of chemically modulated solid–liquid interfacial films represents a rapidly evolving and interdisciplinary field. Continued advancements in experimental characterization, theoretical modelling, and material design are expected to further enhance our ability to control interfacial phenomena at the molecular level. Such progress is crucial for developing adaptive, durable, and high-performance interfacial systems that meet the demands of emerging technologies.

2. Fundamentals of Solid–Liquid Interfacial Chemistry

The solid-liquid interfacial chemistry is that part of chemistry that examines the physical characteristics at the interface between a solid and a liquid and the interactions between the two. The solid-liquid interface is responsible for many processes that are important for all types of chemical reactions, such as adsorption, wetting, dissolution, corrosion, and film formation. The structure and energy of the solid-liquid interface are different from those of the bulk phases of the solid and liquid [1]. Figure 1 describes the key concepts governing solid–liquid interfaces, including interfacial formation, intermolecular interactions, surface chemistry, interfacial thermodynamics, and the structure and dynamics that control interfacial behavior. The fundamentals of solid–liquid interfacial chemistry are shown in Figure 1.

2.1. Physicochemical Nature of Solid–Liquid Interfaces

The interface between the solid and liquid phases comprises locally heterogeneous regions, wherein each part has a different chemical environment compared to the bulk. Molecules in the solid phase and molecules located within the liquid phase interact with each other by a combination of van der Waals forces, electrostatic interactions, hydrogen bonds, and possibly covalent linkages; thus, the spatial arrangement and relative strengths of these interactions dictate how adsorbates attach to the surface of a solid, their orientation, and their movement [2]. The interfacial behavior of solid–liquid systems is further complicated by the presence of surface roughness, crystallographic differences in orientation, and chemical heterogeneity, which can result in the development of vertically or laterally varying properties of the solid–liquid interface, which in turn influences the physical characteristics of a film during its formation and growth [3].

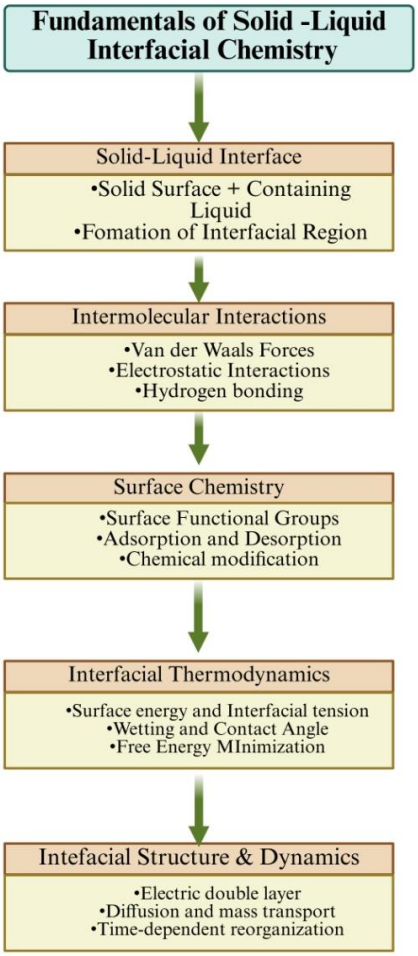

Fig. 1. Schematic representation of the fundamental concepts of solid–liquid interfacial chemistry

2.2. Interfacial Free Energy, Wetting, and Adhesion Phenomena

The free energy of the interface is a hub thermodynamic parameter that connects molecular interactions with macroscopic observables. Any modifications made to the chemical environment of a solid surface will Change its Surface Energies, and therefore Change the Wetting Characteristics of that surface from Hydrophobic to Hydrophilic. Both applications rely on controlling the wetting transition. In

addition to these uses, controlling the interfacial energetics has other uses; for example, controlling the surface energy will also help meet the adhesion requirements in coatings, combinatorial chemistries, and other applications [4].

2.3. Molecular Interactions Governing Interfacial Film Formation

The creation of an interfacial film can be influenced by several factors, such as the attraction between two substances and restrictions on movement due to confinement or fitting into a certain order within the interfacial structure. These factors include the molecular size, shape, polarity, and flexibility of the molecules adsorbed onto the surface. Cooperative interactions between adsorbing molecules create a type of cooperative effect that can result in phenomena such as phase change, orderliness, and multilayering among adsorbed molecules [5].

3. Mechanisms of Interfacial Film Formation

Various types of solids and liquids are formed in an interfacial state. As a result of the molecular interaction between the two materials, several molecular interactions, transport processes, and surface chemical compositions are required. Unlike the transformation of solid–liquid into bulk form, the solid–liquid is less uniform and has a variable effect of confinement, which results in an interfacial film that is not only metastable but also evolves over time [6]. Figure 2 shows oil–water (O/W) and water–oil (W/O) emulsions stabilized by different classes of emulsifiers, including small-molecular surfactants, macromolecular emulsifiers, and solid particle emulsifiers, highlighting their roles in interfacial stabilization.

3.1. Adsorption and Self-Assembly Processes

Adsorption is the primary mechanism at the solid-liquid interface.

The molecules in the liquid move toward the solid and adsorb to the surface when the gain in free energy due to interaction with the surface is greater than the loss of entropy due to confinement. Physisorption occurs through weak intermolecular forces and allows molecules to continuously exchange with the bulk; in contrast, chemisorption occurs through the formation of stronger irreversible bonds [7, 8].

Self-assembly processes provide a second level of structural organization, particularly for amphiphilic molecules, block copolymers, and biomimetic systems. The self-assembly process can result in the spontaneous formation of one or more layers from a pool of these molecules, with the driving force for this organization being the reduction of interfacial free energy, resulting in anisotropic properties in the produced films and defined functional domains [9, 10].

3.2. Role of Surface Functional Groups and Chemical Heterogeneity

Functional groups on surfaces are used as molecular recognition surfaces and are the determining factors in selecting the appropriate substrates to adsorb onto with the appropriate binding energy. Highly acidic or basic surfaces can form electrostatic interactions, whereas polar functionalization provides the opportunity to create hydrogen bonds [11].

The presence of chemical heterogeneity on a substrate surface creates different levels of adsorption density and film structure compared to a chemically uniform surface. While this level of heterogeneity can be used advantageously in applications requiring gradient properties, it can present challenges in achieving reproducibility and accurate predictive design. There is still much research being conducted to understand how the atomic arrangement of a substrate's surface chemistry relates to the film's overall properties [12].

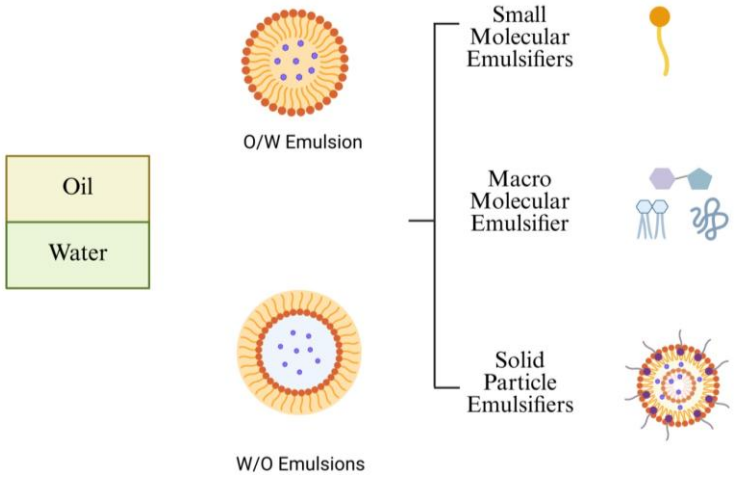

Fig. 2. Schematic illustration of oil-in-water (O/W) and water-in-oil (W/O) emulsions stabilized by different classes of emulsifiers

3.3. Influence of Solvent Properties and Interfacial Solvation

The solvent molecules do not passively observe the formation of the interfacial film; they actively participate. The solvents form structured solvation layers near solid surfaces. The solvation layer can have a different density and correlation with the solid surface than that found in the bulk solvent. Thus, they can compete with the adsorbates for solid surface sites or provide a route for indirect interactions between the surface and film-forming species [13]. The polarity of the solvent, its ability to form hydrogen bonds, and the ionic strength of the solvent have a significant influence on the kinetics and equilibrium of the adsorption of a film onto a solid surface. The hydration forces and ion-specific forces in aqueous systems can dominate interfacial behavior, resulting in non-classical phenomena in the adsorption of a film onto a solid surface [14, 15].

3.4. Kinetics and Thermodynamics of Film Growth

Striking a balance between thermodynamically stable interface structures and kinetically limited non-equilibrium interfaces has implications for interfacial film development.

For example, thermodynamics determines which side of an interface is the most stable film structure; however, the kinetics of a film determine whether the film is created in equilibrium with respect to its upper or lower limit. Therefore, the growth of interfacial films depends on the kinetics of diffusion, surface diffusion, and molecular rearrangements [16].

4. Chemical Modulation Strategies at Solid-Liquid Interfaces

4.1. Surface Functionalization and Chemical Grafting

When surfaces are covalently modified with specific chemical groups, chemical modifications can be achieved at the interface between the solid substrate and liquid phase (Table 1). Examples of these methods include silane chemistry, sulfide bonding, and the use of polymers to coat solid surfaces.

Table 1. Chemical Modulation Strategies for Solid–Liquid Interfacial Films and Their Key Characteristics.

Modulation Strategy	Representative Modifiers / Methods	Nature of Interaction	Tunable Parameters	Stability Characteristics	Representative Applications	References
Surface Functionalization and Chemical Grafting	Silanes, thiols, phosphonates, polymer brushes	Covalent bonding	Surface chemistry, grafting density, chain length	High mechanical and chemical stability	Corrosion protection, adhesion control, biosensing	[17]
Surfactant Adsorption	Ionic and non-ionic surfactants	Non-covalent (electrostatic, hydrophobic)	Concentration, pH, ionic strength	Moderate stability; reversible adsorption	Lubrication, wetting control, detergency	[18]
Polymer Adsorption and Assembly	Polyelectrolytes, block copolymers	Physical adsorption, electrostatic interactions	Molecular weight, charge density, solvent quality	Enhanced steric and electrostatic stabilization	Tribology, antifouling coatings	[19]
Small-Molecule Modifiers	Organic acids, inhibitors, corrosion suppressors	Weak chemical or physical interactions	Molecular structure, surface affinity	Limited long-term stability	Corrosion inhibition, surface passivation	[20]
pH-Responsive Modulation	Weak polyelectrolytes, ionizable ligands	Reversible electrostatic interactions	pH, buffer composition	Dynamic and reversible	Controlled release, smart coatings	[21]
Ionic Strength-Responsive Modulation	Salt-sensitive polymers, charged surfactants	Electrostatic screening effects	Salt type and concentration	Tunable but environment-sensitive	Colloidal stabilization, lubrication	[22]
Redox-Responsive Modulation	Disulfide linkages, redox-active polymers	Reversible covalent or coordination bonds	Redox potential, chemical environment	Stimuli-triggered stability switching	Electrochemical interfaces, drug delivery	[23]
Stimuli-Responsive and Adaptive Films	Multi-responsive polymers, hybrid systems	Combined covalent and non-covalent	pH, temperature, light, redox state	Adaptive, self-regulating stability	Smart surfaces, biomedical and energy systems	[24]

Covalent modification of a surface can create irreversible changes in the surface, including changes in its electrostatic and chemical properties [25].

Grafted or chemisorbed molecules can exhibit significantly greater stability during the washout process than other types of surface modifications. The grafting density and molecular configuration can be systematically adjusted to achieve the desired level of chemical reactivity and thickness of the interfacial film. Surface modifications, when performed properly, are commonly employed in applications such as antifouling, lubrication, and biomodification [26].

4.2. Use of Surfactants, Polymers, and Small-Molecule Modifiers

Surface-active agents, polymeric materials, and small-molecule modifiers interact through reversible adsorption at the solid-liquid interface via non-covalent bonding forces. Surfactants reduce the interfacial tension at the solid-liquid interface, promote the formation of organized films, and increase stability through their capacity for multiple valences [27].

In addition to providing pro-stabilizing features in a system, polymers allow fine adjustment of the packing density and chemical functionality and are a source of secondary stabilization. These systems can reorganize the interfacial layer as needed by changing the conditions. Because of their reversible layers, these systems are self-healing and adaptive [28].

4.3. pH-, Ionic Strength-, and Redox-Responsive Modulation

The interfacial film structure and properties can be modified using chemical stimuli, such as pH, ionic strength, and redox potential. The protonation or deprotonation of ionizable groups alters the charge and conformation of the surface. In addition, changes in ionic strength can affect electrostatic screening and adsorption characteristics. Additionally, redox-active compounds may enable switchable bonding/permeability control mechanisms. This level of control over interfacial dynamics is necessary for the design of sensors/smart coatings and controlled-release systems [29].

4.4. Stimuli-Responsive and Adaptive Interfacial Films

Interfacial films equipped with the ability to respond to stimuli change their structure and function in response to external stimuli. Examples of these external stimuli include temperature, mechanical stress, light, and chemical signals. Stimuli-responsive interfacial films can be considered to have characteristics similar to those of biological interfaces by incorporating various responsive components [30]. Additionally, they can switch between multiple functional states and reorganize and self-repair on a reversible basis, all of which allow them to perform better under changing operational conditions. Nonetheless, the major obstacle facing researchers today when developing such materials is ensuring that they remain responsive for extended periods [31].

5. Stability of Solid–Liquid Interfacial Films

The stability of solid–liquid interfacial films is an important factor in determining their long-term functionality and reliability. Stability comprises three components: mechanical integrity, chemical stability, and the ability to maintain stability over time under changing operating conditions.

Films that are chemically modulated must be able to withstand environmental changes while remaining structurally sound [32, 33]. If one can understand how films degrade and age, then one can estimate the length of service they will have before failure occurs. The stability of solid–liquid interfacial films can also create trade-offs in designs between maintaining stability and providing adequate response and adaptability [34].

5.1. Mechanical and Structural Stability under Static Conditions

The mechanical stability of an interfacial film indicates how well it can maintain itself and adhere to the substrate over a long period of time or with minimal shear. The mechanical stability of a film is mainly affected by three factors: the thickness of the film, the number of molecules packed together in the film, and the strength of the bonds between the molecules at the interface of the film and the substrate [35].

Mechanically stable films have strong crosslinking and multivalent attachment interactions that offer the greatest resistance to failure owing to deformation. A poorly constructed film either peels away from the substrate or breaks apart owing to high internal stress levels.

Therefore, to support the weight of the clipboards and offer protection from falling debris, the film must maintain structural integrity [36].

5.2. Chemical and Environmental Stability

Chemical stability is the ability of an item to remain intact when exposed to solvents, pH changes, oxidative agents, and temperature fluctuations [37]. The chemical composition of the film and chemical bonding at the interface can change as a result of exposure to the environment. The use of chemically resistant functional groups and covalently bonded anchoring systems enhances the stability of these items [38]. Environmental compatibility is critical when handling corrosive or biologically active materials. Therefore, long-term performance relies on advancing methods to reduce the likelihood of chemical deterioration [39].

5.3. Interfacial Aging, Degradation, and Reconstruction

Interfacial films can experience aging over time due to various slow molecular rearrangements, chemical reactions, or desorption processes. The primary degradation mechanisms that can act on an interfacial film are oxidation, hydrolysis, and chain scission. In some instances, there may be sufficient reconstruction or reorganization of the interfacial film to restore functionality, whereas in other instances, gradual performance loss can occur as a result of the aging process [40].

Therefore, to accurately predict the lifetime of materials and optimize their characteristics, it is essential to understand these processes [41].

5.4. Factors Influencing Long-Term Film Integrity

The molecular architecture of the material, the amount of interfacial bonding strength between the components and substrate, the amount of environmental exposure, and the number, location, and size of mechanical constraints influence its long-term integrity.

The high-density packing of materials and strong surface-to-surface interactions result in high durability while at the same time potentially limiting adaptability [42]. The film thickness and crosslinking density also play a role in the degradation resistance. These factors must be considered when designing for both stability and functionality [43].

6. Characterization Techniques for Interfacial Films

Advanced characterization techniques are beneficial for analyzing the characteristics of interfacial films (Table 2). Because the film is very thin at the nanoscale, advanced surface-sensitive methods are required for analysis.

A combination of different techniques would be helpful in providing a full understanding [44]. The use of in-situ techniques is becoming increasingly important for observing dynamic characteristics. Ultimately, to fully understand the relationship between the structure of the film and its performance, it is necessary to characterize the height, thickness, and performance under real-life conditions [45].

6.1. Spectroscopic and Microscopic Approaches

Electron Spectroscopy is used to measure the chemical composition and bonding information of substances. Microscopic Methods are used to study the morphology of a surface at the nanoscale. Atomic Force Microscopy (AFM) is used to study the mechanical and topological properties of a surface. Microscopic and spectroscopic techniques are key techniques for studying interfacial films with molecular-scale to nanoscale clarity [53].

6.2. Surface Force and Interfacial Rheology Measurements

The measurement of Surface Forces provides significant information about Interaction Forces, Adhesion, and Mechanical Responses at the interfaces. Interfacial Rheology measures the viscoelastic behavior of materials under Shear or Confinement of Normal Loads.

These methods are essential for investigating Lubrication and Adhesion phenomena. They are direct connections from the molecular level to the macroscopic level for mechanical performance. Without such measurements, performance cannot be adequately assessed [54].

6.3. In Situ and Operando Characterization Methods

Operando and in situ methods help researchers observe the growth or dissolution of interfacial films when the systems are functioning.

The data acquired from these studies can provide valuable information on the dynamic behavior of systems. Additionally, operando studies can improve our ability to link static characterization with the real-world functions of materials and systems built from them. Studies of this type are essential for all electrochemical and tribological systems, and they provide insights that are not possible through ex situ studies of materials or systems [55].

6.4. Computational and Theoretical Modelling of Interfacial Films

Computational methods provide molecular-level insights into the interfacial behavior of materials. Molecular dynamics provides information on molecular structure, dynamics, and transport [56-58]. Continuum and Multiscale models provide insight into how the behavior of molecules at the atomic level relates to the larger-scale physical properties of materials [59]. Theoretical models have been developed to help researchers anticipate how films behave and how to design them. Researchers often incorporate modelling into the experimental phase of their work [60].

7. Performance Metrics and Functional Implications

Measurable functional outcomes are achieved through the performance metrics of interfacial film properties, which are relevant to specific applications and reflect the requirements of the application (e.g., friction reduction, barrier efficiency, or reactivity control). Chemical modulation is used to optimize the performance of interfacial films [61].

Understanding the relationship between performance and structure will facilitate rational performance design. Performance evaluation assists in selecting materials and engineering methods to optimize performance [62].

Table 2. Summary of key techniques for characterizing solid–liquid interfacial films and their capabilities

Technique Category	Representative Methods	Information Obtained	Spatial/Temporal Resolution	Key Advantages	Limitations	References
Spectroscopic Techniques	FTIR, Raman, XPS, NMR, UV–Vis	Chemical composition, bonding states, molecular orientation, surface functional groups	Molecular-level; ensemble-averaged	High chemical specificity; non-destructive (in some cases)	Limited spatial resolution; often requires dry or vacuum conditions	[46]
Microscopic Techniques	AFM, SEM, TEM, STM, Optical Microscopy	Surface morphology, film thickness, roughness, nanostructure	Nano- to microscale	Direct visualization of interfacial structures	Sample preparation artifacts; limited chemical information	[47]
Surface Force Measurements	Surface Force Apparatus (SFA), Colloidal Probe AFM	Interfacial forces, adhesion, steric and electrostatic interactions	Ångström–nanometer	Quantitative force–distance measurements	Complex experimental setup; model systems required	[48]
Interfacial Rheology	Shear and dilatational rheometry, Quartz Crystal Microbalance (QCM-D)	Viscoelastic properties, film rigidity, adsorption kinetics	Dynamic, time-resolved	Sensitive to weakly bound and soft films	Interpretation can be model-dependent	[49]
In Situ / Operando Methods	In situ AFM, ATR-FTIR, Electrochemical QCM	Real-time film formation, restructuring, and degradation	Time-resolved, molecular to mesoscale	Captures dynamic interfacial processes	Instrumental complexity; limited environments	[50]
Electrochemical Techniques	Cyclic voltammetry, EIS, chronoamperometry	Interfacial charge transfer, redox behavior, film permeability	Time-resolved	Essential for electrochemical interfaces	Indirect structural information	[51]
Computational and Theoretical Approaches	Molecular dynamics, Monte Carlo simulations, continuum modelling	Molecular organization, energetics, transport mechanisms	Atomic to mesoscale (model-dependent)	Mechanistic insight beyond experiments	Accuracy depends on force fields and assumptions	[52]

7.1. Transport, Barrier, and Lubrication Properties

Interfacial films control the transport of ions, molecules, and solvents through an interface barrier layer. Barrier properties are important for both corrosion protection and membrane applications, whereas the boundary film in lubrication creates stable friction and wear [63]. The chemical and physical composition of an interfacial film can significantly affect its ability to transport materials. Optimized interfacial films tend to perform better and last longer than other types of interfacial films [64].

7.2. Adhesion, Friction, and Wear Behavior

The adhesive bond and frictional force are governed by intermolecular interactions and the film's structural properties at its interface. A chemically designed surface can be selected to enhance the bond or maximize slip based on the type of application [65]. The amount of wear experienced is heavily influenced by the stability of the film under mechanical stress. The good tribological

performance of a material is highly responsive to the chemical properties of its interface and can be controlled through the modulation process [66].

7.3. Interfacial Reactivity and Mass Transfer Control

Chemical reactivity is ultimately controlled by how 'interfacial films' control the ability of reactants to react with the surface interface, including catalytic and electrochemical systems, which also determine the rate of a chemical reaction and its products. In addition to controlling mass transport limitations, the design of interfacial chemistry influences energy and catalytic applications, where efficiency is a concern [67].

7.4. Structure–Property-Performance Relationships

To rationally design materials, it is critical to understand the relationship between the molecular structure, interfacial properties, and macroscopic performance. Correlations at all scales of composite materials are complicated by multiscale complexity; however, improvements in characterization and modelling methods allow us to make predictions about the sustainable performance of composites much more effectively. The relationships established in the future will ultimately be the basis for interfacial engineering [68].

8. Applications of Chemically Modulated Interfacial Films

In many technological areas, interfaces comprise chemically modified (functionalized) surfaces (Figure 3). The performance and lifetime of these interfaces can be enhanced by modifying their surface interaction characteristics. Interface design strategies are dictated by application-specific requirements, and through ongoing innovation, these systems continue to expand their functionality. Consequently, these systems will serve as a connecting link between fundamental sciences and applied engineering/development [73]. Figure 3 describes the wide range of possibilities for chemically controlled interface coatings and the ways they can be utilized for biomedical applications, energy and environment technologies, industrial and materials engineering, and advanced functional surfaces, all accomplished due to the ability to alter interface chemistry through a variety of means and make responsive to changes in the environment through the properties of the coating films.

8.1. Tribology and Lubrication Systems

In tribological applications, interfacial films serve as protective boundary layers between two materials, reducing friction and wear. Chemical modulation allows for increased adaptability to different loading and environmental factors. Responsive Films are responsive to the variability of stresses at the interface [69]. This system improves the overall energy efficiency and lifetime of the components through enhanced mechanical strength/efficiency and adaptability to various environmental conditions. These films are essential for both mechanical and industrial applications [70].

8.2. Corrosion Protection and Surface Coatings

Interfacial films protect against corrosive reactions by providing both chemical and physical barriers. By using chemical grafting and responsive coatings, the chances of survival in harsh environments are increased.

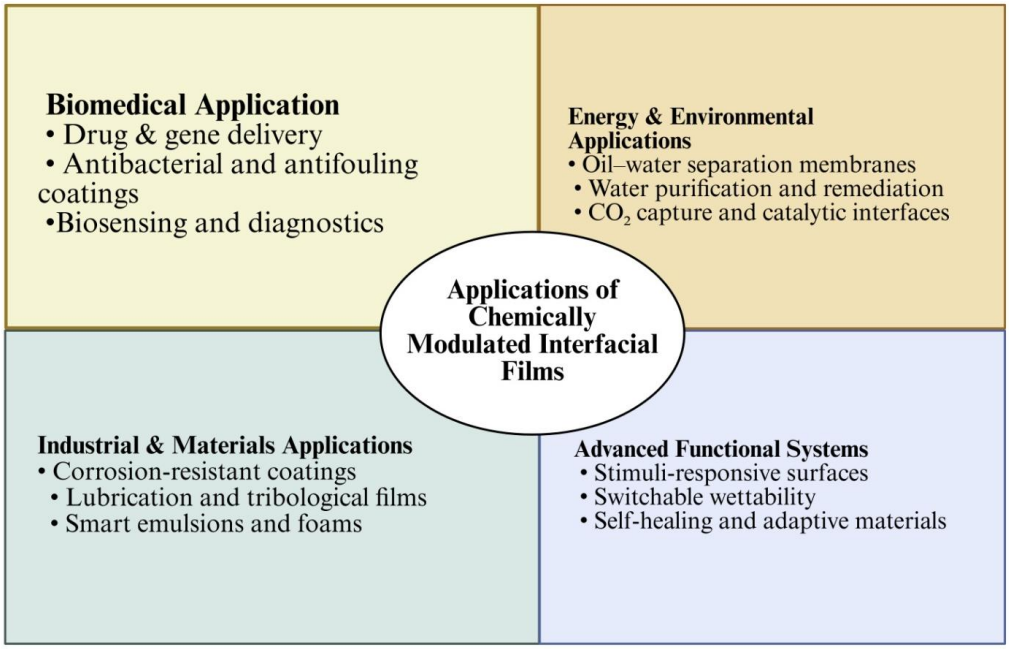

Fig. 3. Overview of applications of chemically modulated solid–liquid interfacial films

Long-term protection can only occur when the integrity of the protective film is preserved. Many infrastructure and marine applications utilize these coatings because of their advanced protection capabilities. An improved interfacial design provides enhanced durability and safety [71].

8.3. Energy Storage, Conversion, and Electrochemical Interfaces

Interfacial Films allow for efficient charge transfer and ion transport through stable interfacial films within electrochemical interfaces. Chemically modulated interfacial films have increased the cycle stability and safety of such devices. In addition to their value in terms of battery, supercapacitor, and fuel cell performance, their application within the interfacial engineering process also enhances the performance of these devices. The importance of Interfacial Engineering in the development of sustainable energy technologies cannot be overstated [72].

8.4. Biomedical, Environmental, and Industrial Applications

Antifouling coatings, drug delivery systems, membrane technology, and industrial processing machinery are examples of potential applications. The compatibility of a film with humans/animals and the environment is an important factor in the production of coatings. Chemical modulation allows purposeful interactions with various types of chemical/biological species, enhancing the performance and safety of coating technology. The ability of these films to be modified for use in numerous ways supports their wide-ranging applications [73].

9. Emerging Trends and Future Perspectives

The field of allenes and similar compounds is developing rapidly. Advances in the design, characterization, and analysis of materials using data science to understand the behavior of interfaces have created new possibilities in interfacial science. Future materials will be adaptable, multifunctional, and sustainable. Addressing these limitations will facilitate the widespread use of these materials. Ongoing interdisciplinary collaborations are necessary for continued development in this area [74].

9.1. Smart and Multifunctional Interfacial Films

Interfacial smart films incorporate sensing, actuation, and self-healing properties. The integrated multi-properties allow for the concurrent manipulation of mechanical, chemical, and transport characteristics. These multifunctional materials utilize the biologically based architecture of living organisms to create intelligent interfaces with enhanced adaptive capabilities. Therefore, they will be a major driving factor for future developments in this area [75].

9.2. Integration of Machine Learning and Predictive Design

Complex interfacial datasets are analyzed with increasing frequency using machine learning to predict the performance of materials. Data-driven models allow new materials to be discovered and optimized faster than previous methods, such as heuristics [76]. The use of machine learning in combination with experimental and simulation techniques enhances the efficiency of designing new materials. Predictive analytics tools limit trial-and-error design processes. Therefore, the interfacial engineering paradigm is changing owing to the implementation of machine learning [77].

9.3. Challenges, Knowledge Gaps, and Research Opportunities

Multiscale characterization, long-term stability, and scalability are some of the key challenges in this field. However, our understanding of the dynamic and non-equilibrium behaviors of these systems is still lacking. Bridging laboratory experiments with their field applications remains a challenge. Therefore, addressing these issues will provide many new research opportunities and will be accomplished through coordinated efforts between experimentalists, theorists, and computational scientists. [78].

10. Conclusions

Chemical modulation is a promising method for creating, maintaining, and controlling solid-liquid interfaces for multiple applications. Chemical modulation provides a wide variety of possibilities for the design and application of solid-liquid interfacial films by modifying chemically functionalized surfaces, molecular architecture or structural arrangements, and environmental stimuli-induced adaptations. Covalent and non-covalent chemical modulation approaches provide long-lasting stability, flexibility, and responsiveness under different environmental conditions. The ability of interfacial films to sustain mechanical forces, chemical environments, and aging effects is the critical factor that currently limits their stability. Recent advancements in in situ engineering analysis and computational modelling have led to a greater understanding of the molecular-level properties of these complex systems, which will be utilized to establish structure-performance relationships that guide the rational design of interfacial films to enhance their smartness, durability, and performance in future technologies. The combination of chemical design, advanced characterization techniques, and predictive Modelling will be key to the continued growth of the smart, durable, and high-performance Solid-Liquid

Interfacial Films required by future technologically oriented markets.

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