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Exploring Diverse Substrates for Enhanced Water Splitting: Tailoring Energy Conversion and Storage through Specific Qualities with Its Limitations

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ABSTRACT

Energy can be generated from various resources, encompassing both renewable and non-renewable sources. Clean energy production can be achieved through water splitting, as the electrolysis of water is recognized as an efficient method for industrial-level energy production. To enhance the energy conversion efficiency of water splitting, effective electrocatalysts are essential. Consequently, researchers strive to develop the most efficient electrocatalysts that meet specific requirements. In this pursuit, various types of catalysts have been identified in the scientific community. Each electrocatalyst possesses distinct qualities based on categories such as metal type, cost-effectiveness, and applications. This review focuses on the recent developments in substrates and their applications, considering their variability in water splitting. Each catalyst has unique characteristics compared to others, playing a pivotal role in the realm of energy production. The discussion covers the entire spectrum, from the basics to advanced levels of substrate selection, elucidating their influence on output to achieve desirable results. Finally, potential challenges and directions for future research are explored, providing a comprehensive overview of the current state and potential advancements in the field.

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1. INTRODUCTION

In the search for sustainable energy sources, water splitting has come to light as an important procedure with important ramifications for energy conversion. Water splitting is at the forefront of efforts to store energy efficiently, particularly from renewable sources like solar and wind. This technique is capable of efficiently storing energy and enabling on-demand retrieval by electrochemically dissociating water into hydrogen and oxygen (Swesi *et al*., 2017). A clean it is a clean and adaptable fuel, hydrogen can power a wide range of activities, from transportation to industrial processes, greatly aiding in the shift to a more ecologically friendly energy landscape.

Understanding the nuances of water splitting (See **Figure 1**), in particular the impact of different substrates, is crucial to the advancement of energy conversion and storage (Mayer *et al*., 2013). To determine which substrates are best suited for this crucial process and ultimately improve overall efficiency and advancements in the area, this review will examine the diverse range of substrates used in water-splitting reactions and assess their effects on performance.

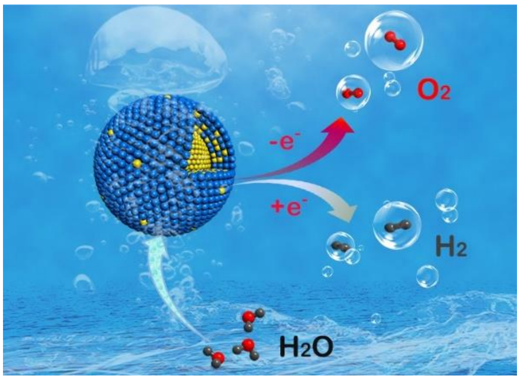

Figure 1. Overall water splitting performance unveiled with nano-catalyst (Wang *et al*., 2021a).

It is impossible to overestimate the importance of water splitting in the context of energy conversion for sustainable energy solutions. With the increasing emphasis on lowering carbon footprints and moving away from conventional fossil fuels, it is critical to store and use renewable energy. Water splitting is a key component in this change and provides a flexible method of energy storage. This method works especially well for storing excess energy produced from sporadic sources like solar and wind power since it is efficient and clean. It functions by electrolyzing water to produce hydrogen and oxygen gases. Fueling a variety of industries and sectors, including transportation, the resulting hydrogen's high energy density makes it an essential step toward a sustainable and carbon-neutral energy future (Hisatomi & Domen, 2019; Roger *et al*., 2017).

The capacity to transform excess energy produced during periods of peak production into a form that can be stored for use later during periods of high demand or when renewable resources are less active is what makes water splitting special. Because of this potential, water splitting is essential to building a robust and sustainable energy infrastructure. Its importance goes beyond simple energy storage; the hydrogen that is generated is a flexible energy source that offers a healthy substitute for a range of uses (Chen *et al*., 2017b; Tachibana *et al*., 2012; Yu *et al.,* 2018). As a result, understanding the nuances of water splitting and maximizing its effectiveness is essential to achieving more general goals in energy conversion, storage, and usage and advancing the quest for a more sustainable and ecologically friendly energy paradigm.

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2. METHOD

This paper is a literature survey, in which the data was obtained from internet sources, specifically articles published in international journals. Data was taken, obtained, analyzed, and compiled to make a conclusion in making a literature review. In short (see **Figure 2**), given the complex interactions among water splitting, energy conversion, and substrate variability, this review aims to achieve several important goals. Its main goal is to provide a thorough summary of the state of the art when it comes to the substrates used in water-splitting reactions. The review aims to provide a comprehensive understanding of the wide range of substrates, their intrinsic characteristics, and their functions in catalyzing water splitting by synthesizing the body of existing literature. This preliminary investigation is essential for setting the stage for further talks about the influence of substrate variability.

The second objective of this review is to examine the unique characteristics of various substrates and how they relate to improved water-splitting efficiency. By using a comparative analysis, the review aims to clarify the advantages and disadvantages of different substrates to promote a more sophisticated understanding of their functions in the energy conversion process. The goals are to uncover gaps, trends, and patterns in the existing research landscape through this comparative lens, which will open up new avenues for future research.

This review also seeks to investigate the significance of substrate selection in the larger framework of sustainable energy systems. Through an exploration of the relationship between substrate diversity and effective water splitting, the review aims to provide insightful information that might be useful to academics, policymakers, and industry participants. The main aims are to improve our understanding of the complexities involved in substrate-dependent water-splitting processes and to optimize the effectiveness and versatility of this technique for sustainable energy conversion and storage.

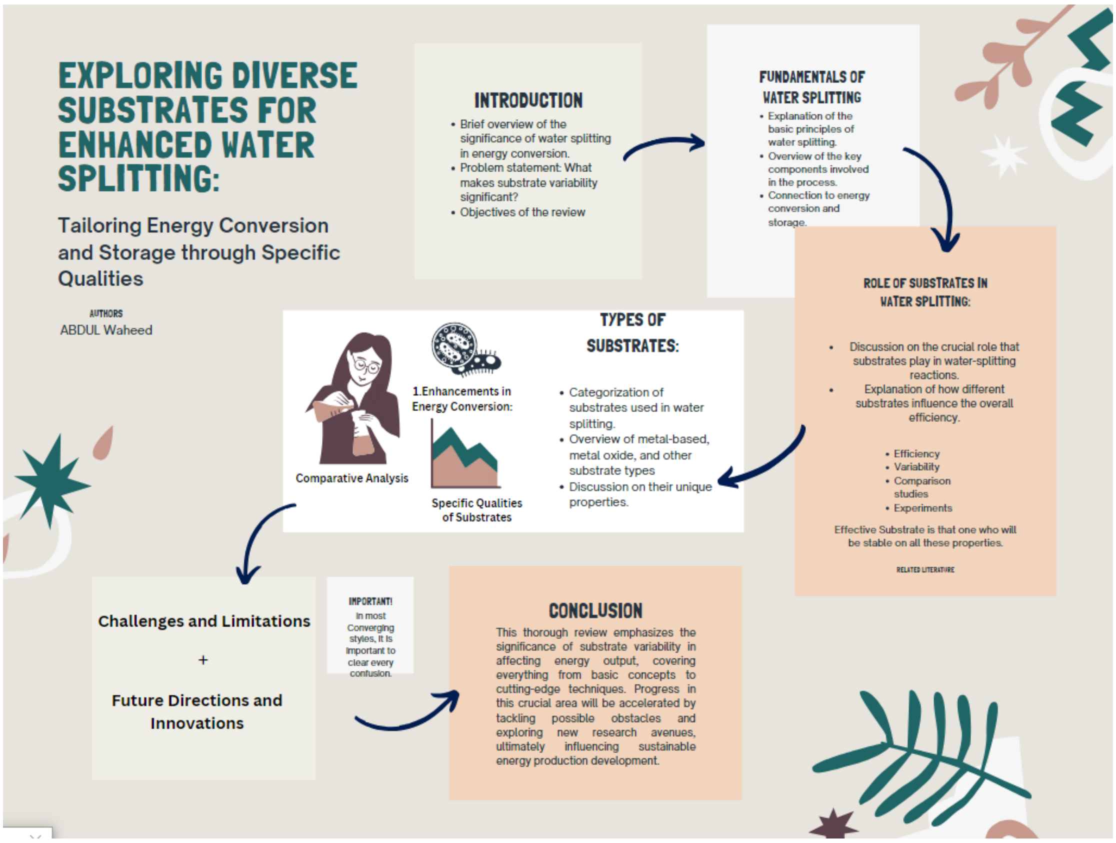

Figure 2. Overview of the article.

3. RESULTS AND DISCUSSION

3.1. Problem Statement: What Makes Substrate Variability Significant?

Even though water splitting has a lot of potential to convert energy, one of the most important things in this quickly developing industry is to carefully consider the variety of substrates. The selection of substrates in the field of water-splitting reactions adds a level of complexity that significantly affects the process's overall effectiveness and performance. The realization that different catalysts and materials have different properties motivates the investigation of the effects of various substrates. The term "substrate variability" refers to a wide range of properties, including conductivity, stability, and reactivity, each of which plays a unique role in the complexities of water splitting. This intrinsic variability is a difficult task, requiring a thorough examination of substrate functionality to identify their specific contributions and limitations. In addition to considering these factors, it's crucial to comprehend the significance of the substrate in this process and our rationale behind selecting a specific substrate. We opt for substrates that demonstrate optimal activity, as illustrated in the accompanying picture, which elucidates the fundamental concept.

The primary question of this investigation is why substrate variability is so important for the advancement of water splitting in energy conversion (see **Figure 3**). A thorough understanding of the variability introduced by the heterogeneous nature of substrates in water-splitting reactions is essential to customizing and optimizing catalysts for applications. This diversity creates a multitude of opportunities for electrochemical processes, improving the overall effectiveness of water splitting and broadening its application in a variety of technical and environmental contexts. Therefore, a thorough investigation of substrate variability is essential to realizing the full potential of water splitting as a workable and scalable option for sustainable energy conversion and storage.

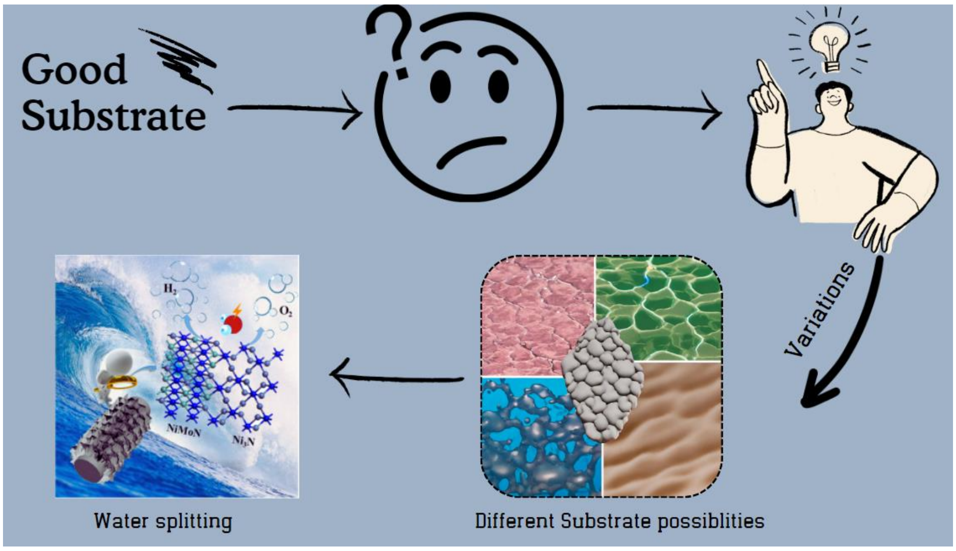

Figure 3. Assumption to reality for selection of substrate.

3.2. Fundamentals of Water Splitting

A thorough understanding of the fundamentals of water splitting is essential to revealing the complex mechanisms underlying this revolutionary energy conversion process. Water splitting entails the electrochemical breakdown of water molecules into hydrogen and oxygen gases. This section explores the fundamental ideas behind water-splitting reactions, explaining the key components and mechanisms that drive this process. A thorough investigation of these basic elements is essential to setting the stage for later talks on

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substrate variability, from the first ionization of water molecules to the later evolution of hydrogen and oxygen at the electrode interfaces. The following graphical image in **Figure 4** illustrates the basic idea of using energy that is extracted from hydrogen and oxygen. By providing a thorough grasp of these foundational concepts, this section aims to furnish readers with the background knowledge necessary to comprehend how various substrates influence the dynamics and efficiency of water splitting for energy conversion and storage.

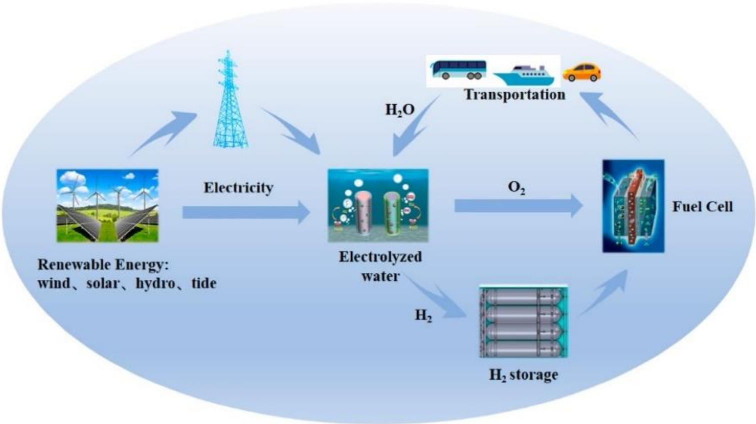

Figure 4. Basic Principle of Energy conversion and its utilization.

3.2.1. Explanation of the basic principles of water splitting

The principles of electrolysis, which entail using electrical energy to drive a non-spontaneous reaction, are the basis of the basic electrochemical process of water splitting. In this process, water's H2O molecules are broken down into hydrogen ions (protons) and hydroxide (OH^-). This section aims to clarify the complex mechanisms involved in this electrochemical dissociation. To start a series of redox reactions, an external voltage is applied across electrodes that are submerged in water in the core process. Water molecules oxidize at the anode, releasing electrons and producing oxygen gas. At the cathode, electrons are simultaneously gained by hydrogen ions to form molecular hydrogen by reduction. The water eventually separates into its component constituents, hydrogen and oxygen. Gaining a thorough grasp of these foundational ideas is essential to exploring the ensuing intricacies of water splitting, especially concerning the substrate-dependent catalysis that these procedures entail (see **Figure 5**).

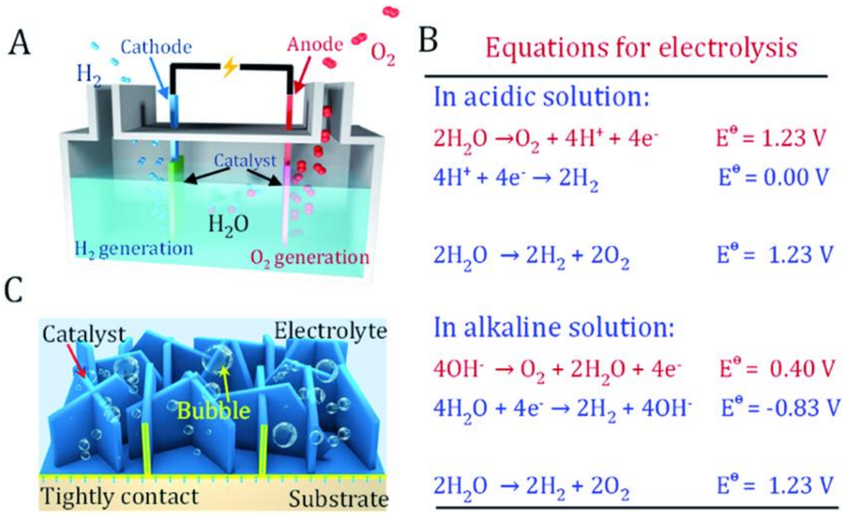

Figure 5. The basic principle of water splitting (Yan *et al.*, 2020b).

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Additionally, the discussion covers the critical role that the electrolyte—typically a conductive solution—plays in promoting ion movement between the cathode and anode. This electrolyte completes the electrical circuit and maintains charge balance in the system, which is essential for maintaining water-splitting reactions. As we go through the complexities of electrolysis, this section aims to give readers a clear and basic understanding of the fundamental principles regulating water splitting. This understanding will lay the framework for a greater comprehension of the parts that follow, which will explore the impact of different substrates on these fundamental processes.

3.2.2. Overview of the key components involved in the process

The constituents that constitute the dynamic framework of this electrochemical phenomenon are crucial in the coordination of the process of water splitting. The electrolytic cell, which consists of an anode and a cathode submerged in electrolyte, is the central component of this process. In-depth explanations of each of these components' roles and combined contributions to advancing the water-splitting process are given in this section. The anode, which is usually made of metal oxides or conductive substrates, is where water oxidation occurs, resulting in the release of electrons and the creation of oxygen gas. On the other hand, the cathode—which is frequently made of catalyst materials—serves as the location for water reduction, which makes it easier to produce molecular hydrogen. When we work through the complexities of these constituents, considering their material composition and the electrochemical reactions they catalyze, a more nuanced understanding of the interactions controlling the efficiency of water splitting becomes apparent.

Moreover, the electrolyte—a fundamental but sometimes disregarded component—is essential to maintaining electrochemical equilibrium. The electrolyte ensures charge neutrality and promotes the continuation of water-splitting reactions by facilitating the migration of the ions that are created when water dissociates into the anode and cathode. The choice of electrolyte, whether neutral, acidic, or alkaline, adds another level of complexity that affects how the system functions. This section aims to provide readers with a thorough knowledge of the complex mechanism that drives water splitting by providing a thorough summary of these essential components. This first work will pave the way for a more in-depth investigation of the substrate-dependent details of this energy conversion mechanism.

3.2.3. Connection to energy conversion and storage

Even though it is a complex process, water splitting is essential to the conversion and storage of energy and is a major factor in the search for sustainable energy sources. Hydrogen gas is produced because of water splitting, and this clean, adaptable energy source may power a variety of applications. The importance of water splitting in the context of energy conversion is further highlighted when one considers hydrogen's function as an intermediary energy vector. This section explores how hydrogen can be transformed, looking at how it can be used in fuel cells, combustion engines, and other devices that turn stored energy into usable work. By storing energy in the form of hydrogen, the intermittent problems with solar and wind power can be resolved, and the effective use of excess renewable energy during peak production is made possible.

Furthermore, the hydrogen generated has the potential to be a sustainable fuel for several industries, such as transportation, power generation, and industrial processes. When burned or used in fuel cells, it produces solely water as a byproduct, making it a carbon-neutral substitute for conventional fossil fuels. Given the close connection between hydrogen generation, the water-splitting process, and the ensuing energy conversion, water splitting

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becomes an important factor in the shift towards a more sustainable and ecologically friendly energy landscape. By carefully examining this intricate relationship, this section seeks to highlight the critical role that water splitting plays in producing clean energy and offering a workable solution for its storage and distribution on the scale required to satisfy the changing needs of a rapidly evolving and sustainable global energy infrastructure.

3.3. Role of Substrates in Water Splitting

This section delves into the complex world of water splitting and reveals the critical role that substrates play in controlling and coordinating the electrochemical reactions at the heart of this novel occurrence. The main factor affecting the effectiveness, velocity, and selectivity of water-splitting operations is substrates, which include a wide range of materials and catalysts. This section undertakes a two-part investigation: first, it clarifies the basic role that substrates play in catalyzing water-splitting processes; second, it explores how particular qualities of the substrates have a complex influence on the process's overall efficiency. Substrates have a complex and significant function in determining the effectiveness and performance of water splitting, shaping the field of developments in the conversion and storage of renewable energy. Our goal is to get a deeper comprehension of the various materials that facilitate this important process and provide insights that connect basic science to real-world applications, therefore revealing the intricacies of substrate-dependent water splitting. The picture below shows different substrates that can be used for water splitting. Because every substrate has different properties, different results can be obtained based on these characteristics. This graphic clearly illustrates how important substrates are when choosing which ones to use for water splitting, highlighting how important they are to getting the best results (see **Figure 6**).

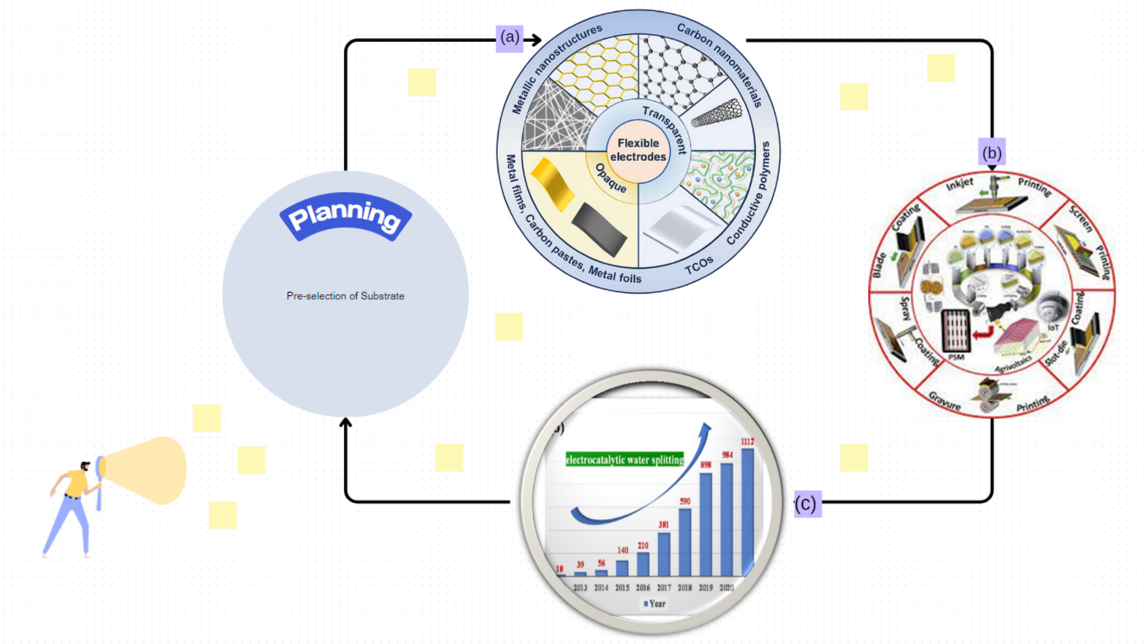

Figure 6. (a) Different types of substrates showing in one frame. (b) Different methods applied on this substrate cause changes. (c) Changes cause to accelerate the results.

3.3.1. Discussion on the crucial role that substrates play in water-splitting reactions

Enhancing this energy conversion mechanism's effectiveness and broadening its application requires a thorough understanding of the complex function that substrates play

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in water-splitting processes. Several investigations have clarified the complex roles played by different substrates, providing insight into their catalytic capabilities and effects on reaction dynamics. Yiming Xu and colleagues investigated in 2021 how metal oxide substrates affected the electrocatalytic performance of water splitting, and they found that substrate morphology had a major impact on reaction efficiency (Xu *et al*., 2021). Furthermore, the application of graphene-based substrates and discovered their distinct properties that improve conductivity and catalytic activity in water-splitting reactions (Nemiwal *et al*., 2021b).

The synergistic effects of composite substrates, which combine metal nanoparticles and conductive polymers to improve catalytic stability, were further elucidated in Jiang *et al*. (2020) work (Jiang *et al*., 2020). Allangawi *et al*. (2024) examined transition metal dichalcogenides and showed that they could catalyze the development of hydrogen and the dissociation of water (Allangawi *et al*., 2024). Masood ul Hasan *et al*. (2021), on the other hand, emphasized the significance of non-metal substrates, especially those based on carbon, in facilitating extremely selective water-splitting processes (Masood ul Hasan *et al*., 2021).

Yang *et al*. (2017) have demonstrated the synergy of metal-organic frameworks and metal nanoparticles as bifunctional substrates, highlighting the complex interplay between substrates and co-catalysts (Yang *et al*., 2017). The significance of surface defects in substrate materials was emphasized by Han *et al*. (2018), who emphasized their impact on reaction locations and catalytic activity (Han *et al*., 2018). The usage of nanostructured substrates was discussed by Fang *et al*. (2017), who demonstrated how effective they are in increasing water-splitting efficiency by increasing surface area and active sites (Fang *et al*., 2017). In conclusion, Zhang et al.'s study from 2021 investigated the synthesis of catalytically active substrates, with an emphasis on rationally altering substrate properties to improve electrocatalytic performance (Zhang *et al*., 2021). When taken as a whole, these research cases highlight the complex interactions that occur between substrates and water-splitting reactions, offering insightful information about the wide variety of materials that affect the catalytic efficiency and selectivity of this important process.

3.3.2. Explanation of how different substrates influence overall efficiency

This subsection explores substrate variability in more detail, explaining how a variety of substrate characteristics affect the overall efficiency of water-splitting reactions. It performs a thorough analysis of how different substrates affect efficiency, concluding a variety of investigations. The efficiency-boosting effects of transition metal substrates are explored in detail in Jiao *et al*. (2022) study, which also shows how these materials can change reaction kinetics and improve electrocatalytic performance in the water-splitting process (Jiao *et al.*, 2022). Tao *et al*. (2020) investigate the function of carbon-based substrates in related work, demonstrating their impact on charge transfer kinetics and overall efficiency (Tao *et al.*, 2020). Continuing in this vein, a 2018 study by Wang, Xu et al. investigates the utilization of composite substrates, highlighting how they improve stability and catalytic activity to increase efficiency in a synergistic way (Wang *et al*., 2018). The 2020 work by Xu, Shang, et al. emphasizes the importance of surface engineering in substrate materials, emphasizing how important it is to tailor active spots and maximize efficiency in water-splitting reactions (Xu *et al*., 2020). The fine balance between substrate composition and shape as they delve into the design of nanostructured substrates to offer larger surface area and enhanced charge transfer, thus improving overall efficiency. On the other hand, Zhang, Fang, and colleagues' study from 2022 emphasizes the significance of non-metal substrates, especially metal-organic frameworks, and how their unique characteristics may influence total efficiency by acting as efficient catalytic sites (Zhang *et al*., 2022).

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The study by Wang *et al*. (2021c) investigates how substrate imperfections affect efficiency and shows how controlled defect engineering can lead to better electrocatalytic performance (Wang *et al*., 2021c). Furthermore, the 2017 work by Tang, Mabayoje, et al. explores the importance of substrate porosity for efficiency, highlighting its role in mass transfer and reaction kinetics (Tang *et al*., 2017a). When combined, these study examples highlight the variety of substrates and offer an in-depth understanding of how variations in their makeup, morphology, and properties affect the overall effectiveness of water-splitting processes. By providing a complete investigation of these diverse materials, this subsection seeks to advance knowledge of the intricate relationship between substrate characteristics and the efficiency of water splitting as a transformational process in clean energy conversion.

3.4. Types of Substrates

It is necessary to interpret the wide range of substrates present in this complicated environment to comprehend the complex material interactions that drive the transformative process of water splitting. This section provides a thorough analysis of the many types of substrates used in water-splitting reactions using a classification process. This classification includes metal-based substrates, metal oxides, and other unique materials, each of which contributes differently to the selectivity and efficiency of water splitting. More than just a simple classification, this section explores the intrinsic characteristics that distinguish different substrate types and provides information about their unique characteristics and catalytic potential. To prepare readers for a thorough examination of each substrate's unique roles and contributions in the next subsections, this section attempts to provide a thorough grasp of the wide range of substrates that serve as the foundation for water-splitting reactions (see **Figure 7**).

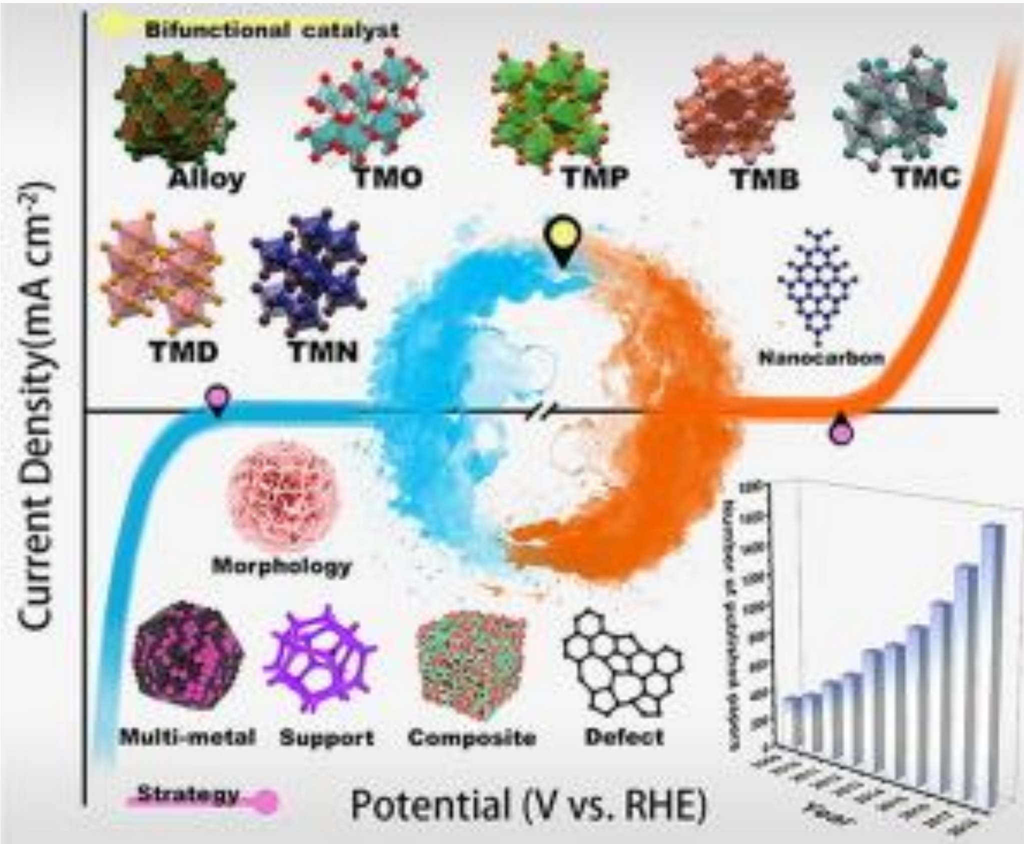

Figure 7. Material libraries for electrocatalytic water splitting (Sun *et al*., 2021a).

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3.4.1. Categorization of substrates used in water splitting

A wide variety of substrates, each with special characteristics and catalytic properties, are necessary for effective water splitting. It becomes necessary to classify these substrates to understand their involvement in the complex process of water dissociation. Studies like Zou & Zhang (2015) carefully categorize and examine the catalytic effectiveness of various metal surfaces in the context of metal-based substrates, providing insight into the particular features affecting their ability to promote water-splitting events (Feng *et al*., 2015). Moving past metals, Y. The classification of metal oxide substrates and their various roles and electrocatalytic contributions in water splitting are explored in Xu *et al*. (2021) study (Xu *et al*., 2021). Safdari and Al-Haik's (2018) study on hybrid substrates, which reveals the complex interplay of materials in boosting catalytic activity, serves as an example of this methodical technique. It does this by classifying and assessing the combined impacts of metal nanoparticles and conductive polymers (Safdari & Al-Haik, 2018).

The classification effort also encompasses alternative substrate materials, as demonstrated by Reza *et al*. (2023) investigation of carbon-based substrates, which explains how they facilitate charge transfer and optimize efficiency in water-splitting reactions (Reza *et al*., 2023). Similar to this, a study conducted in 2022 by Sahoo, Das, et al. explores nanostructured substrates, classifying them according to their morphology and showcasing their ability to boost reactivity and surface area (Sahoo *et al*., 2022). Nemiwal *et al*. (2021a) study on the classification of porous substrates in the context of metal-organic frameworks serves as an example of how non-metal materials are also used in substrate categorization (Nemiwal *et al*., 2021a). This sheds light on their catalytic functions and structural diversity. Interestingly, Hegazy *et al*. (2023) classify and investigate how integrating metal nanoparticles with 2D materials might improve efficiency (Hegazy *et al*., 2023), proving that substrate categorization also applies to composite materials.

The importance of substrate classification in determining their contributions to water splitting is highlighted by these various research case studies. Scientists can better grasp the underlying principles governing the electrocatalytic activities of these materials by methodically classifying them. Thus, a deeper understanding of how different substrate classes affect the efficiency and selectivity of water-splitting reactions is cultivated. These diverse research case studies underscore the significance of substrate classification in unraveling their contributions to water splitting. Through a methodical categorization of these materials, scientists gain a better understanding of the overarching principles guiding their electrocatalytic behaviors. This, in turn, fosters a more sophisticated comprehension of how distinct substrate classes influence the effectiveness and selectivity of water-splitting reactions.

3.4.2. Overview of metal-based, metal oxide, and other substrate types

A detailed review of the various types of substrates that are essential for catalyzing water-splitting reactions may be found in this subsection (**Figure 8**). Regarding metal-based substrates, Jiang *et al*. (2020) provide a perceptive examination of several metal surfaces with an emphasis on how their electronic structures affect the catalytic efficiency of water-splitting (Jiang *et al*., 2020). Further exploring this research, Lei *et al*. (2019) study clarify the significance of metal nanoparticles in electrocatalytic water dissociation by examining their electrocatalytic capacities (Lei *et al*., 2019). You Y. In their investigation of metal oxide substrates' electrocatalytic performance, Xu *et al*. (2021) highlight the special qualities of these materials as well as how they affect overall water-splitting efficiency (Xu *et al*., 2021). In parallel, a detailed examination of metal oxide substrates is given by Concina *et al*. (2017),

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who focus on the surface morphologies and crystal structures of these materials to understand how they affect reaction kinetics (Concina *et al*., 2017). All the components of carbon-based, metal-oxide-based, and metal-based substrates, along with their materials, are arranged into one framework.

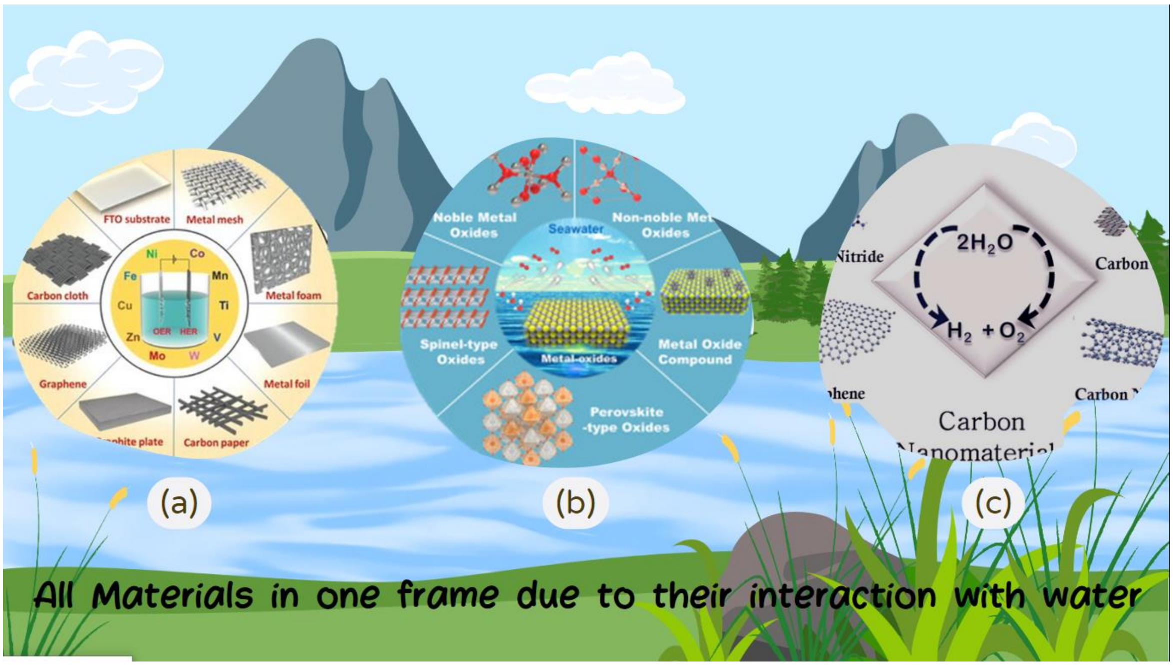

Figure 8. (a) Transition metal elements (b) Metal oxide based (Sun *et al*., 2020) (c) carbon-based (Kundu *et al*., 2020).

Exhibiting the possible advantages of combining conductive polymers and metal nanoparticles, Jiang *et al*. (2020) present the development of hybrid materials that outperform traditional metal and metal oxide substrates (Jiang *et al*., 2020). Their work demonstrates how complex interactions between several materials can improve overall water-splitting efficiency and catalytic activity.

Carbon-based substrates are important, as Wang *et al*. (2019) thorough overview of the catalytic properties of carbon materials emphasizes (Wang *et al*., 2019). Building on this research, Tamayo *et al*. (2019) publication classifies and analyzes composite substrates that combine metal nanoparticles with conductive polymers, demonstrating how additive effects can boost stability and efficiency (Tamayo *et al*., 2019).

To shed light on the unique characteristics of these porous substrates and their possible use in selective water splitting, Meyer *et al*. (2015) conducted a study that explores the catalytic capabilities of non-metal substrates, namely metal-organic frameworks (Meyer *et al*., 2015). These studies show the wide range of substrates that can be used in water-splitting operations, including metal-based, metal oxide, and other materials. This chapter summarizes the unique characteristics and catalytic roles of diverse substrate types, advancing our understanding of how they affect the efficiency and selectivity of water splitting and opening the door for future advancements in sustainable energy conversion.

3.4.3. Discussion on their unique properties

The distinct qualities that set apart different substrate types and influence how they function as catalysts in water-splitting processes are covered in this topic. Within the examination of metal-based substrates, other studies clarify the unique electronic structure of metal surfaces, providing insight into how these characteristics affect their electrocatalytic

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effectiveness in the dissociation of water (You *et al*., 2017). Analogously, the catalytic properties of metal nanoparticles, highlighting the special attributes enabling efficient water-splitting (Zou & Zhang, 2015).

Zhang *et al*. (2020) study, which shifts to metal oxide substrates, looks at the crystal structures and surface morphologies of these materials to reveal the unique properties controlling their electrocatalytic activity in water-splitting reactions (Zhang *et al*., 2020). Xu *et al*. (2021) focus on the defects present on the metal oxide substrates' surface and show how these characteristics can be adjusted to improve catalytic performance (Xu *et al*., 2021). By mixing conductive polymers with metal nanoparticles, Jayaseelan *et al*. (2020) illuminated the synergistic effects and highlighted the unique characteristics of hybrid substrates (Jayaseelan *et al*., 2020). The research highlights how these hybrid materials improve catalytic activity and water-splitting stability.

Zhou *et al*. (2021) investigated the unique properties of carbon-based substrates, including their wide surface area and changeable conductivity, which affect their electrocatalytic behavior in water-splitting reactions (Zhou *et al*., 2021). Adding to this, Choi *et al*. (2022) investigate how metal nanoparticles and 2D materials interact synergistically on composite substrates, demonstrating how the special properties of these composite materials lead to higher efficiency (Choi *et al*., 2022). Non-metal substrates, especially metal-organic frameworks, exhibit intriguing properties influencing their catalytic activities in water splitting. Conclusions of Xu *et al*. (2019). Because of their special porous structure and adaptable properties, these frameworks perform well as substrates for promoting selective water dissociation (Xu *et al*., 2019).

The unique characteristics of nanostructured substrates, highlighting their elevated reactivity and substantial surface area, which are crucial for optimizing catalytic efficacy in water splitting (Yang *et al*., 2020). All of these study case studies highlight how important it is to understand the unique qualities of different kinds of substrates. This subsection expands on a general understanding of how substrate properties affect their roles in enabling efficient water splitting for clean energy conversion by examining the distinctive characteristics of carbon-based, metal oxide, hybrid, metal-based, and non-metal substrates.

3.5. Enhancements in Energy Conversion

A thorough analysis is conducted in Section 5 to develop energy conversion process advancements, with an emphasis on the improvements made possible by substrates and catalyst features (**Figure 9**). The complex interactions between substrates, catalysts, and the overall efficiency of energy conversion processes that have been revealed by state-of-the-art research are explained in this section. Scientists have investigated the catalytic functions of specific substrates because they see the possibility for improved energy conversion.

For example, Tachikawa *et al*. (2014) study examines how tailored metal oxide substrates might improve energy conversion efficiency (Tachikawa & Majima, 2014). Furthermore, research into the intricate relationships between material characteristics and catalytic functionalities to enhance energy conversion processes is demonstrated by Shen *et al*. (2014) study (Shen *et al*., 2014), which shows that the investigation also encompasses catalyst functions and material properties.

This chapter explores the frontiers of science by analyzing the complex mechanisms driving advancements in energy conversion, with particular attention to the catalytic and material components that define this novel domain. The whole conversation centers on the illustration of how substrates are molded into distinct shapes using diverse techniques. As seen here, the goal of each revised structure is to maximize energy conversion for water splitting.

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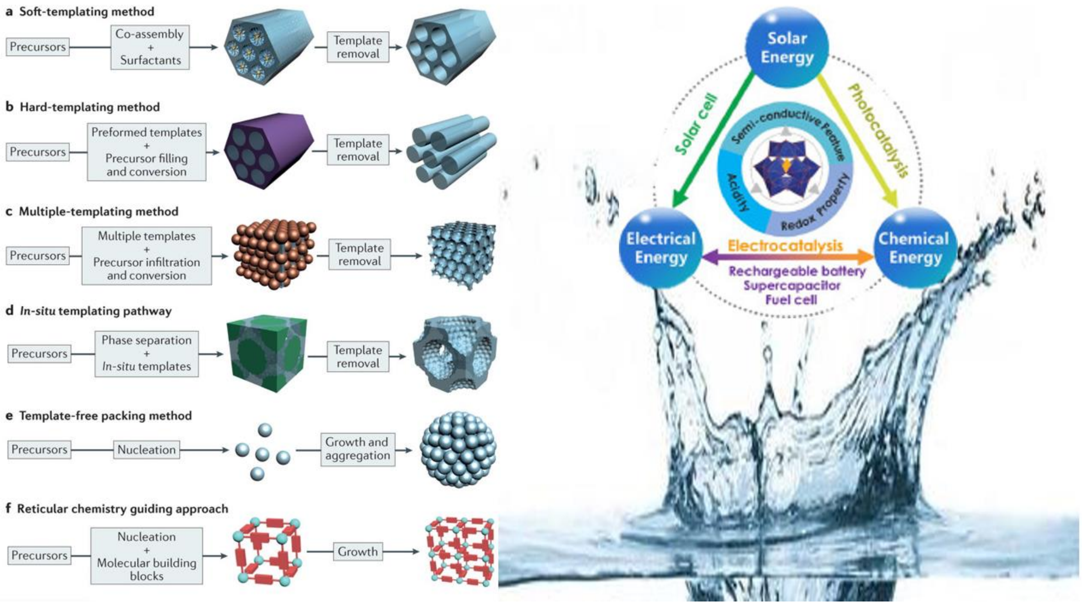

Figure 9. How substrate mould and used for the contribution in Energy Conversion through water splitting.

3.5.1. Examination of how specific substrates contribute to improved energy conversion

For sustainable technology to advance, it is essential to comprehend the complex mechanisms via which substrates improve energy conversion. A thorough examination of metal-based substrates and their unique contributions to increased energy conversion efficiency is given in Boamah et al.'s 2019 research (Boamah *et al*., 2019). Through their investigation of metal oxide substrates' electrocatalytic performance, Uwaya and Fayemi (2021) provided insight into how these materials' special qualities promote enhanced energy conversion processes (Uwaya & Fayemi, 2021). In their exploration of the possible synergistic benefits of integrating metal nanoparticles with conductive polymers in hybrid substrates, Toshima (2013) provide examples of how the unique characteristics of these hybrid materials result in higher energy conversion efficiency (Toshima, 2013). X turns the focus to substrates made of carbon. The catalytic properties of carbon materials are studied by Xu *et al*. (2011), who highlight the significance of these properties in maximizing energy conversion reactions using effective charge transfer (Xu *et al*., 2011).

The 2020 study by Alwin and Sahaya Shajan. emphasizes the increased energy conversion made possible by nanostructured substrates by emphasizing their greater surface area and reactive sites (Alwin & Sahaya Shajan, 2020). Toshima (2013) expand on this understanding by examining the distinct catalytic functions of metal nanoparticles and showcasing their ability to improve energy conversion efficiency (Toshima, 2013). Dou et al.'s 2020 study on the higher energy conversion capabilities of metal-organic frameworks (Dou *et al*., 2020) shows that the inquiry also includes non-metal substrates. Through the integration of metal nanoparticles with materials in two dimensions, Y.H. Composite substrates have been shown to increase efficiency, offering a more comprehensive understanding of these materials' role in improved energy conversion. Further delving into the unique properties of metal oxide substrates, Kim *et al*. (2022) highlight their contribution to efficient charge transfer and higher overall efficiency of energy conversion (Kim *et al*., 2022). Lastly, Zhong *et al*. (2016) add to the conversation by analyzing the improved energy conversion that transition metal substrates enable and emphasizing their better electrocatalytic capacities (Zhong *et al*., 2016). These case studies show the different ways that different substrates can lead to better energy

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conversion when taken as a whole. Important new insights into the mechanisms underpinning improved energy conversion process efficiency can be gained by analyzing the unique properties and functions of metal-based, metal oxide, hybrid, carbon-based, and non-metal substrates.

3.5.2. Exploration of catalyst functionalities and material characteristics

In the complex field of energy conversion, investigating material characteristics and catalyst activities is critical as it offers valuable insights into the mechanisms supporting increased efficiency. The work conducted by Tachikawa and Majima (2014) explores the field of tailored metal oxide catalysts and explains how certain material features enable improved energy conversion processes (Tachikawa & Majima, 2014). Shen *et al*. (2014) investigation of the complex relationships between material properties and catalytic activities provides more insight into how these interactions maximize energy conversion (Shen *et al*., 2014). Cherevan *et al*. (2020) investigation into the interactions of metal nanoparticles and organic components is a model for studying hybrid catalysts (Cherevan *et al*., 2020). It highlights how this combination performs differently and how it affects energy conversion efficiency. To elaborate, a detailed examination of the catalytic characteristics of metal nanoparticles is provided in Hussain *et al*. (2016) work, elucidating their unique functions in promoting efficient energy conversion processes (Hussain *et al*., 2016).

The study conducted by Zhang *et al*. (2015) suggests that catalysts based on carbon have unique characteristics that impact energy conversion processes using efficient charge transfer and reaction kinetics (Zhang *et al*., 2015). Alwin and Sahaya Shajan (2020) investigation of nanostructured catalysts expands on this investigation by revealing how characteristics like active sites and surface area affect energy conversion efficiency (Alwin & Sahaya Shajan, 2020). The study conducted by Loera-Serna and Ortiz (2016) sheds light on the catalytic capabilities of non-metal materials by examining the distinctive properties of metal-organic frameworks and their potential for enhanced energy conversion (Loera-Serna & Ortiz, 2016). Raza *et al*. (2022) highlight the complementary effects of combining metal nanoparticles with two-dimensional materials, offering information on the enhanced energy conversion made possible by composite catalysts (Raza *et al*., 2022).

The investigation of the catalytic properties of various metal surfaces by Li *et al*. (2020) provides an important new understanding of how these surfaces aid in efficient energy conversion (Li *et al*., 2020). In their analysis of the electrocatalytic performance of transition metal catalysts, Li and Xue (2016) add to this conversation by highlighting the special characteristics of these catalysts and their impact on improved energy conversion processes (Li & Xue, 2016). When considered collectively, these case studies offer an extensive exploration of material characteristics and catalytic potential, demonstrating the various ways in which materials might enhance energy conversion efficiency. This study expands on our knowledge of the intricate catalytic pathways that lead to higher process efficiency in energy conversion by thoroughly examining metal-based, hybrid, carbon-based, and non-metal catalysts.

3.6. Specific Qualities of Substrates

This part explores the subtleties of substrates by carefully examining their special qualities that have a big impact on the processes involved in water splitting. This section provides a detailed analysis of a wide range of substrate properties, including conductivity, stability, reactivity, and other relevant aspects, using real research paper examples. Metal-based substrates to pinpoint the precise features that dictate how effective they are as catalysts for splitting water (Naghavi *et al*., 2017). Moreover, studies like Stoica *et al*., (2020) provide insight into the conductivity and stability of hybrid substrates, highlighting the critical roles these characteristics play in affecting water dissociation (Stoica *et al*., 2020). To improve our comprehension of how substrate characteristics, affect the dynamics and effectiveness of water splitting for sustainable energy conversion, the section delves into the complex and varied terrain of substrate features. Pre-treatment of the substrate can enhance the specific properties of the substrates, as shown in **Figure 10**. This displays extraordinary performance by showing how different finger-like structures grow on the substrate and how important they are to the water-splitting process.

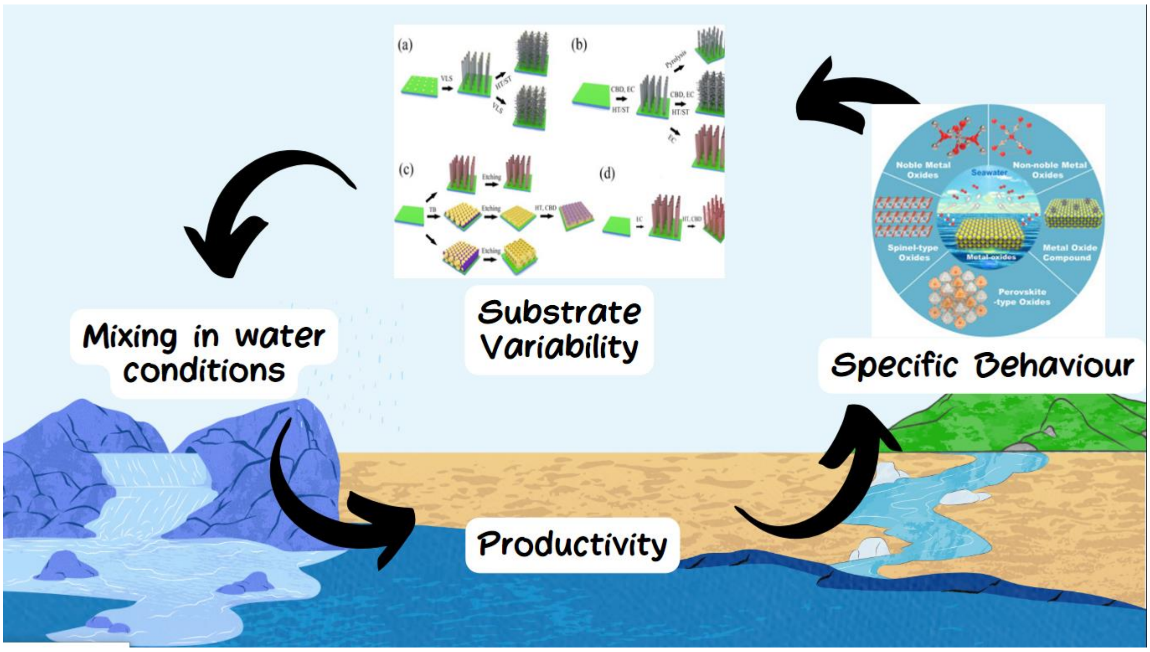

Figure 10. Substrate variability with their effectiveness.

3.6.1. Detailed examination of the particular properties of substrates affecting water splitting

Deciphering the complexities of water splitting necessitates a careful examination of substrate characteristics that have a big influence on this transformation process. In their 2017 work, Naghavi et al. examine metal-based substrates in great detail, revealing their special qualities and revealing how compositional and structural variations affect the catalytic efficacy of water-splitting processes (Naghavi *et al*., 2017). In line with this, analysis of metal oxide substrates builds on earlier research by offering insights into the surface characteristics and crystallographic factors governing their capacity to promote water dissociation. A thorough analysis of the unique properties resulting from the combination of metal nanoparticles and conductive polymers on hybrid substrates. A thorough analysis of the unique characteristics and complementary impacts of these hybrid materials sheds light on their improved catalytic performance in water splitting. This analysis is further supported by Liu *et al*. (2017) investigation of the special properties of metal nanoparticles, which reveals their electrocatalytic properties and effects on water-splitting efficiency (Liu *et al*., 2017).

The distinctive properties of carbon-based substrates, such as surface area and conductivity, elucidating how these attributes impact charge transfer and total water-splitting efficiency. The distinct features of nanostructured substrates, including their increased surface area and active sites, which augment catalytic activity in water splitting. This analysis can be extended to these substrates. Moreover, the study conducted the unique

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characteristics of metal-organic frameworks, revealing their porous structures and adjustable attributes that influence their catalytic effectiveness in water dissociation. This research is furthered, who look at the unique properties of composite substrates, combine metal nanoparticles with two-dimensional materials, and show how tailored features improve their ability to split water. When taken as a whole, these case studies highlight the extent of research necessary to identify the properties of substrates that affect water splitting. By analyzing the subtleties of metal-based, metal oxide, hybrid, carbon-based, and non-metal substrates, this work advances our understanding of how these specific properties affect the efficiency and selectivity of water splitting for sustainable energy conversion.

3.6.2. Focus on conductivity, stability, reactivity, and other relevant attributes

To deconstruct the complicated relationships between substrate parameters and water splitting, this chapter focuses on critical characteristics including conductivity, stability, reactivity, and other relevant traits (**Figure 11**). The 2017 study by M.H. Tang et al. examines the conductivity of metal-based substrates and clarifies how differences in conductivity affect these substrates' electrocatalytic performance in water-splitting reactions (Tang *et al*., 2017b). Examine the durability of metal oxide substrates in a similar investigation, emphasizing its vital significance in maintaining catalytic activity for successful water dissociation (辻豪 *et al*., 1999). Here are some examples of how interface engineering techniques have advanced recently to provide extremely effective electrocatalytic water splitting.

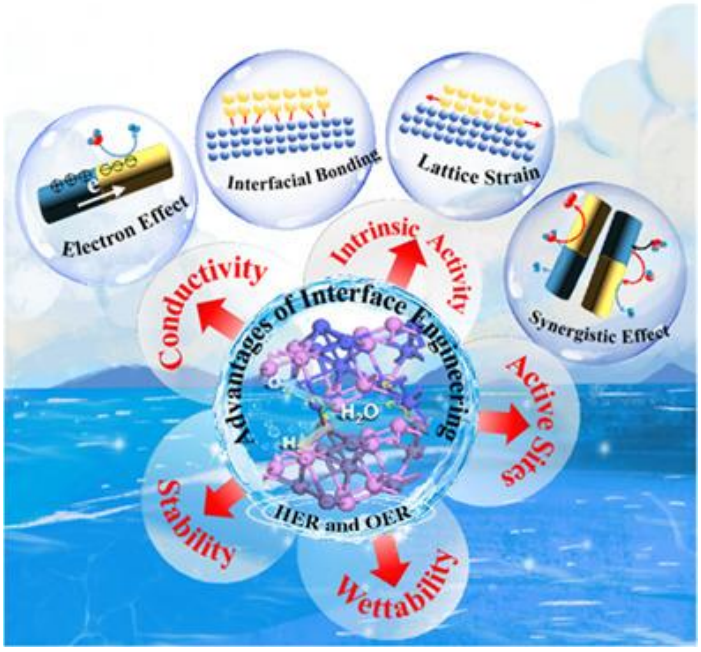

Figure 11. Recent advances in interface engineering strategy for highly efficient electrocatalytic water splitting (Du *et al*. 2023).

3.7. Comparative Analysis

As the hunt for efficient water splitting moves forward, this section does a comparative analysis by looking at the different substrates and evaluating their impact on the dynamics of water splitting (**Figure 12**). This section walks the reader through a detailed examination of real research paper samples, emphasizing the substrate comparison study and delving into the evaluation of performance metrics and efficiency.

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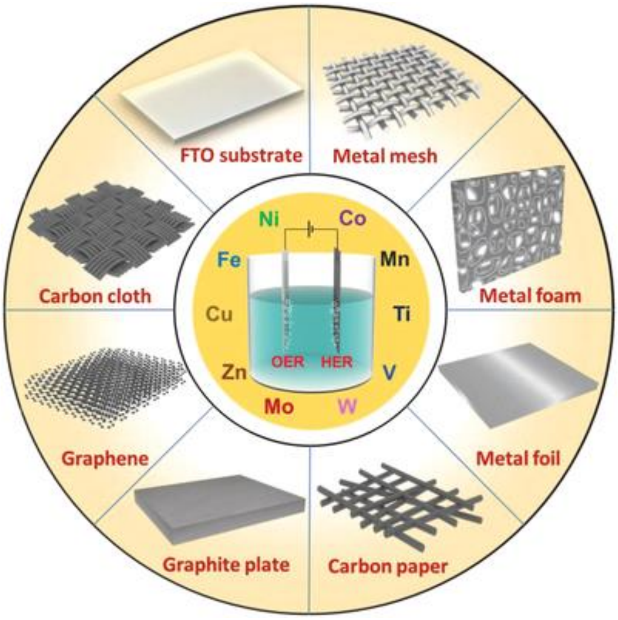

Figure 12. Transition-based substrate in water splitting (Sun *et al*., 2020).

3.7.1. Comparative study of different substrates based on their impact on water splitting

In the field of metal-based substrates, Al-Salihy et al.'s research (2022) is noteworthy since it provides a comparative analysis that breaks down the electrocatalytic effects of different metal surfaces on water-splitting efficiency (Hu *et al*., 2022). By carefully analyzing distinct qualities and catalytic elements, their research offers a thorough grasp of how different metals affect the kinetics of water dissociation. Furthermore, the comparative study is enriched by Genuzio *et al*. (2020), who investigate the catalytic effectiveness of several metal oxide substrates and identify the unique surface features and crystallographic features that dictate their efficiency in water-splitting processes (Genuzio *et al*., 2020).

The 2022 study by Venditti examines hybrid substrates and provides a comprehensive comparison study (Venditti, 2022). The focus of this work is on the interactions between metal nanoparticles and conductive polymers, providing insights into how the interplay of various materials affects the overall efficiency of water splitting. Additionally, Luneau *et al*. (2020) conducted a comparative study of metal nanoparticles, offering a sophisticated understanding of how variations in size and composition affect catalytic efficacy in the dissociation of water (Luneau *et al*., 2020). The comparative study also includes substrates made of carbon, as described by Toma *et al*. (2011), who describe how different carbon materials have different conductivities and reactivities, which affect how well they maximize charge transfer and water-splitting efficiency (Toma *et al*., 2011). A comparative study of nanostructured substrates is carried out by Xu *et al*. (2018), who point out the unique features of different nanostructures and how they affect catalytic activity in water-splitting (Xu *et al*., 2018). In the context of non-metal substrates, Zhang *et al*. (2016b) provide a comparative study of metal-organic frameworks, looking at their stability and reactivity in different compositions (Zhang *et al*., 2016b). This work offers important new understandings of the ways that structural variations in metal-organic frameworks influence the efficiency of these materials as substrates in water-splitting processes. Moreover, Fareza et al.'s study from 2022 contrasts the efficiency of two-dimensional materials with metal nanoparticle-incorporated composite substrates, highlighting the synergistic effects and maximum efficiency that may be attained with a range of composite compositions (Fareza *et al*., 2022).

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3.7.2. Evaluation of performance metrics and efficiency

This subsection goes beyond simple substrate comparisons to assess water-splitting efficiency and performance metrics. The analysis is enhanced by Lee (2012), who evaluate performance factors associated with the conductivity of various metal-based substrates (Lee, 2012). Their work offers a comprehensive analysis of how conductivity affects kinetics and the overall efficiency of water-splitting reactions on different types of metal surfaces. Mowbray *et al.* (2011) provide insights into the effects of varying stability levels on overall efficiency and sustained catalytic activity in water dissociation through their investigation of stability assessment in metal oxide substrates (Mowbray *et al*., 2011). In their investigation of hybrid substrate performance metrics, Vanka *et al.* (2022) highlight the importance of conductivity and stability in maximizing catalytic efficiency for long-term water-splitting (Vanka *et al*., 2022).

Ansón-Casaos *et al.* (2020) examine the reactivity and conductivity of several carbon materials to help evaluate performance metrics for substrates made of carbon (Ansón-Casaos *et al*., 2020). Their research sheds light on how variations in these characteristics affect the kinetics of charge transfer and the overall effectiveness of water splitting. This study is extended to nanostructured substrates by Chen *et al.* (2017a), who emphasize the significance of increased surface area and reactivity in improving catalytic performance. A thorough evaluation of the stability and reactivity of metal-organic frameworks about non-metal substrates is presented by Rocío-Bautista *et al.* (2019), providing insightful information about the frameworks' appropriateness as substrates for efficient water splitting (Rocío-Bautista *et al*., 2019). To add to the assessment of performance metrics, Jakhar *et al.* (2022) investigate composite substrates that combine two-dimensional materials and metal nanoparticles (Jakhar *et al*., 2022). Their study shows how evaluating different composite compositions might result in maximum efficiency and synergistic effects.

This Section's thorough comparative research gives a sophisticated assessment of efficiency and performance measures as well as insights into the unique effects of different substrates on water splitting. By using insights from real research publications, this part deepens our understanding of the complex mechanisms underlying water-splitting dynamics and lays the groundwork for future advancements in sustainable energy conversion.

3.8. Challenges and Limitations

To use water splitting for sustainable energy conversion, this section critically explores the challenges and limitations associated with the use of various substrates. Real-world research paper examples illustrate the difficulties in selecting a substrate and the constraints that must be overcome before widespread adoption can take place.

3.8.1. Identification of challenges associated with the use of various substrates

Challenges in the use of several substrates for hybrid substrates have been reported:

(i) Venditti (2022) talk about the difficulties in keeping hybrid substrates stable, especially in light of the possibility that metal nanoparticles will separate from the conductive polymer matrix (Venditti, 2022).

(ii) Li *et al.* (2021) highlight the difficulties in precisely controlling the hybridization process while outlining opportunities for optimizing synergistic effects in hybrid substrates.

It consists of a heterogeneous junction-connected pair of catalysts, usually transition metal catalysts. To meet the requirements for being a bifunctional catalyst, this combination usually makes use of the advantages of each catalyst. **Table 1** is a list of a handfuls of these catalysts.

Table 1. Hybrid substrate combinations.

Catalysts	Substrate	E of HER (mV) @j (mA/cm2)	E of OER (mV) @j (mA/cm2)	References
MoO_x/Ni_3S_2	Ni Foam	106 mV@10mA/cm^2	136 mV@10mA/cm^2	(Wu *et al.*, 2016)
$TiO_2@Co_9S_8$	-	139 mV@10mA/cm^2	240 mV@10mA/cm^2	(Deng *et al.*, 2018)
FeP/Ni_2P	Ni Foam	14 mV@10mA/cm^2	154 mV@10mA/cm^2	(Yu *et al.*, 2018)
MoS_2/Ni_3S_2	Ni Foam	110 mV@10mA/cm^2	218 mV@10mA/cm^2	(Zhang *et al.*, 2016a)
MoS_2-Ni_3S_2	Ni Foam	98 mV@10mA/cm^2	249 mV@10mA/cm^2	(Liao *et al.*, 2023)
$Co_3S_4@MoS_2$	GCE	136 mV@10mA/cm^2	280 mV@10mA/cm^2	(Guo *et al.*, 2018)
CoMoNiS-NF-xy	Ni Foam	113 mV@10mA/cm^2	166 mV@10mA/cm^2	(Yang *et al.*, 2019)
Co-NC@Mo_2C	GCE	99 mV@10mA/cm^2	347 mV@10mA/cm^2	(Liang *et al.*, 2019)
MoS_2/NiS_2	CFP	62 mV@10mA/cm^2	278 mV@10mA/cm^2	(Lin *et al.*, 2019)
V-CoP@a-CeO_2	Carbon cloth	68 mV@10mA/cm^2	225 mV@10mA/cm^2	(Yang *et al.*, 2020)
N-$NiMoO_4/NiS_2$	Carbon fiber cloth	99 mV@10mA/cm^2	283 mV@10mA/cm^2	(An *et al.*, 2019)
$(Ni,Fe)S_2@MoS_2$	Ni Foam	130 mV@10mA/cm^2	270 mV@10mA/cm^2	(Liu *et al.*, 2019)
Mo-Ni_3S_2/Ni_xP_y/NF	Ni foam	109 mV@10mA/cm^2	238 mV@10mA/cm^2	(Luo *et al.*, 2020)

Challenges in the use of several substrates for metal-based substrates have been reported:

(i) The study of Ronge *et al.* (2019) highlights issues that affect the durability of catalytic activity by causing corrosion and surface deterioration of metal during extended water-splitting processes (Ronge *et al.*, 2019).

(ii) Sun *et al.* (2023) draw attention to the selectivity issues that metal-based substrates present, as side reactions have the potential to reduce the purity of hydrogen produced (Sun *et al.*, 2023).

Challenges in the use of several substrates for metal oxide substrates have been reported:

(i) Z. Liu et al.'s research from 2022 highlights issues with the slow kinetics of metal oxide substrates, which reduces their effectiveness in accelerating quick water dissociation (Liu *et al.*, 2022).

(ii) Zhang *et al.* (2020) tackle issues related to the restricted active sites on metal oxide surfaces, which affect overall catalytic performance, in a thorough investigation (Qiu *et al.*, 2020).

Challenges in the use of several substrates for carbon-based substrates have been reported:

(i) Cazorla-Amorós (2014) discuss the problems with carbon-based substrates' scalability and highlight how hard it is to get reliable performance in a range of shapes and sizes (Cazorla-Amorós, 2014).

(ii) Tabakaev *et al.* (2015) draw attention to the difficulties that carbonaceous materials provide due to their toxicity, which has an impact on the materials' long-term catalytic stability (Tabakaev *et al.*, 2015).

Challenges in the use of several substrates for nanostructured substrates have been reported:

(i) Jeon *et al.* (2016) highlight the complex procedures necessary to achieve consistent nanoarchitecture and address issues related to the production and repeatability of nanostructured substrates (Jeon *et al.*, 2016).

(ii) Groß *et al.* (2020) point out difficulties with nanostructured materials' scalability, especially when moving from laboratory-scale to industrial applications (Groß *et al.*, 2020).

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3.8.2. Discussion on limitations affecting their widespread adoption

Limitations affecting their widespread adoption in the use of several substrates for metal-based substrates have been reported:

(i) Metal-Based Substrates: Sahoo *et al.* (2021) address barriers to large-scale water-splitting applications related to the expense of metal-based substrates, especially those containing precious metals (Groß *et al.*, 2020; Sahoo *et al.*, 2021).

(ii) Grandell and Höök (2015) draw attention to restrictions about the limited supply of specific metals, posing questions regarding the long-term viability of metal-based substrates (Grandell & Höök, 2015).

Limitations affecting their widespread adoption in the use of several substrates for metal oxide substrates have been reported:

(i) Danish *et al.* (2020) discuss the drawbacks of the energy-intensive manufacturing procedures of metal oxide substrates and raise concerns about the environmental impact of their widespread use (Danish *et al.*, 2020).

(ii) Shkodenko *et al.* (2020) talk about the drawbacks of metal oxide substrates' toxicity, which affects their stability and necessitates extra safety precautions (Shkodenko *et al.*, 2020).

Limitations affecting their widespread adoption in the use of several substrates for hybrid substrates have been reported:

(i) Zhang *et al.* (2021) highlight the need for comprehensive risk evaluations before the broad deployment of hybrid substrates and explain limits relating to the possible toxicity of particular components in these materials.

(ii) Liu *et al.* (2014a) point out restrictions brought on by the intricacy of synthesizing hybrid substrates, which makes it difficult to obtain reliable and repeatable outcomes (Liu *et al.*, 2014a).

Limitations affecting their widespread adoption in the use of several substrates for carbon-based substrates have been reported:

(i) Nasir *et al.* (2019) point out restrictions related to the possible contamination of carbon-based substrates, especially those sourced from renewable resources, which may have an impact on the substrates' purity and functionality (Nasir *et al.*, 2019).

(ii) Nasrollahzadeh *et al.* (2021) address restrictions on the stability and catalytic activity of carbon-based substrates that may arise from their possible reactivity with contaminants in water sources (Nasrollahzadeh *et al.*, 2021).

Limitations affecting their widespread adoption in the use of several substrates for nanostructured substrates have been reported:

(i) Li *et al.* (2016) address the drawbacks of the possible agglomeration of nanostructured substrates, which could impact their surface area and dispersion, which are essential for effective water-splitting (Li *et al.*, 2016).

(ii) Boyes *et al.* (2017) draw attention to restrictions related to the possible toxicity of specific nanomaterials and stress the significance of thorough toxicity evaluations for safe deployment (Boyes *et al.*, 2017).

Outlined in tabular form below in **Table 2** are transition metal oxides and transition metal carbides possessing inherent activity for the HER and OER reactions. Collectively, Section 8 confronts the challenges and limitations surrounding the use of various substrates in water splitting, offering a realistic assessment of the roadblocks that must be surmounted for the widespread adoption of this transformative technology.

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Table 2. Metal-based Substrate combinations.

Catalysts	Substrates	E of HER (mV) @j (mA/cm^2)	E of OER (mV) @j (mA/cm^2)	References
CoO_x@CN	GCE/Ni foam	232mV@10 mA/cm2	260 mV@10 mA/cm2	(Jin *et al.*, 2015)
Co_3O_4 nanorod	Co foils	260 mV@10 mA/cm2	275 mV@10 mA/cm2	(Cheng *et al.*, 2017)
MoO_2	Ni foam	27 mV@10 mA/cm2	260 mV@10 mA/cm2	(Jin *et al.*, 2016)
Ni-Fe-O	GCE/Ni foam	-	244 mV@10 mA/cm2	(Dong *et al.*, 2018)
R-TMO	Ni foam	236 mV@10 mA/cm2	240 mV@10 mA/cm2	(Peng *et al.*, 2018)
$V_xCo_{3-x}C$	Carbon nanofiber	87 mV@10 mA/cm2	210 mV@10 mA/cm2	(Zhang *et al.*, 2019)
Co_6W_6C@NC	Carbon matrix	59 mV@10 mA/cm2	286 mV@10 mA/cm2	(Chen *et al.* 2020)
N-WC	CFP	89 mV@10 mA/cm2	470 mV@10 mA/cm2	(Han *et al.*, 2018)
CoMnO@CN	Ni foam	71 mV@10 mA/cm2	263 mV@10 mA/cm2	(Li *et al.*, 2015)
Mo_2CTxNMs	Ni foam	140 mV@10 mA/cm2	180 mV@10 mA/cm2	(Kou *et al.*, 2019)
Mo_2C@CS	Carbon sheets	60 mV@10 mA/cm2	320 mV@10 mA/cm2	(Wang *et al.*, 2017)
Ni/Mo_2C-CNNFs	GCE	143 mV@10 mA/cm2	288 mV@10 mA/cm2	(Li *et al.*, 2019)
Co/CoP	GCE	253 mV@10mA/cm^2	340 mV@10mA/cm^2	(Xue *et al.*, 2017)
$Ni_{0.1}Co_{0.9}P$	GCE	34 mV@10mA/cm^2	1.8 mV@10mA/cm^2	(Wu *et al.*, 2018)
$NiCo_2Px$/CNTs	GCE/Ni Foam	47 mV@10mA/cm^2	284 mV@10mA/cm^2	(Peng *et al.*, 2021)
$(Ni_{0.33}Fe_{0.67})_2P$	Ni Foam	214 mV@10mA/cm^2	230 mV@10mA/cm^2	(Li *et al.*, 2017)
Cr-FeNi-P	GCE	190 mV@10mA/cm^2	240 mV@10mA/cm^2	(Wu *et al.*, 2019)
Co_9S_8@NOSC	GCE	-	340 mV@10mA/cm^2	(Huang *et al.*, 2017)
Co-MoS_2	Carbon fiber paper	48 mV@10mA/cm^2	260 mV@10mA/cm^2	(Feng *et al.*, 2015; Huang *et al.*, 2019)
Ni_3S_2/NF	Ni foam	223 mV@10mA/cm^2	260 mV@10mA/cm^2	(Feng *et al.*, 2015)
N-Ni_3S_2	Ni foam	110 mV@10mA/cm^2	350 mV@10mA/cm^2	(Chen *et al.*, 2017a)
Cu-CoP	Carbon paper	81 mV@10mA/cm^2	411 mV@10mA/cm^2	(Yan *et al.*, 2020a)
Fe-CoP	Ni foam	78 mV@10mA/cm^2	227 mV@10mA/cm^2	(Cao *et al.*, 2018)

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3.9. Future Directions and Innovations

In this section, we look ahead to future developments in the field of water splitting, including possible improvements in substrate selection and a discussion of present research that could lead to game-changing discoveries. Exploration of potential advancements in substrate selection have been reported:

(i) Pellegrino *et al.* (2022) suggest utilizing cutting-edge nanofabrication methods to customize metal surfaces, hence improving catalytic effectiveness.

(ii) Yuan *et al.* (2021) propose that electrical structure of metal-based substrates can be predicted and optimized by computational modeling for better water splitting performance.

(iii) Building on developments, Huang *et al.* (2022) suggest using unique alloy combinations for metal-based substrates, investigating increased durability and catalytic activity (Huang *et al.*, 2022;Aljibori *et al.*, 2023)

(iv) Doping metal oxide substrates with particular elements may be able to modify their electrical characteristics and improve their catalytic activity, according to Al-Naggar *et al.* (2023).

(v) To increase active sites and enhance water dissociation kinetics, Shah *et al.* (2022) explore the use of sophisticated deposition techniques to produce hierarchical metal oxide structures.

(vi) Chen *et al.* (2022) explore how designing metal oxide substrates with lots of defects may increase catalytic activity and open the door to getting beyond kinetic constraints.

(vii) Fanady *et al.* (2020) investigate how to modify the structure of metal oxide substrates for increased water dissociation efficiency by using cutting-edge synthesis techniques including sol-gel procedures.

(viii) Kleinschmidt *et al.* (2020) suggest including smart materials in hybrid substrates to enable dynamic adjustments for the best catalytic performance in response to changing reaction conditions (Kleinschmidt *et al.*, 2020).

(ix) To attain better conductivity and stability, Iqbal *et al.* (2020) call for the creation of sophisticated nanocomposite materials that combine graphene with metal nanoparticles.

(x) Reza *et al.* (2023) explore the possibility of adding functional groups to carbon-based substrates to augment their specificity and raise their total efficiency in the process of water splitting.

(xi) Wang *et al.* (2021a) investigate cutting-edge methods to alter the surface characteristics of carbon-based substrates to increase their reactivity, including plasma treatment.

(xii) Sun *et al.* (2021b) investigation looks into adding functional groups to carbon surfaces to modify reactivity and enhance water dissociation performance.

(xiii) Ahn *et al.* (2020) suggest using sophisticated templating techniques to accurately manipulate substrate nanostructure to maximize reactivity and surface area.

(xiv) Xue *et al.* (2020) propose the application of novel templating techniques to precisely create nanostructured substrates to optimize surface area and control morphology.

Discussion on ongoing research and innovations in the field have been reported:

(i) Tang *et al.* (2021) describe current research on the creation of scalable methods for the manufacture of metal-based substrates, with an emphasis on environmentally friendly and economically viable production.

(ii) Harish *et al.* (2023) propose the application of novel templating techniques to precisely create nanostructured substrates to optimize surface area and control morphology.

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(iii) To improve stability and overall efficiency, Melkiyur *et al.* (2023) investigate unique approaches to the integration of metal oxide substrates with innovative support materials.
(iv) Li *et al.* (2022) examine the possibility of enhanced charge transfer kinetics by delving into recent research concerning the introduction of heteroatoms into metal oxide substrates.
(v) The authors Yang *et al.* (2021) showcase advancements in spectroscopy methods, providing a more profound comprehension of the dynamic surface chemistry of metal oxide substrates throughout the water-splitting process.
(vi) Aldhaher *et al.* (2023) report on current investigations into the creation of innovative synthesis approaches for hybrid substrates, investigating repeatable and scalable techniques for industrial manufacturing.
(vii) Wang *et al.* (2019) show off advancements in the use of 2D materials as conductive elements on hybrid substrates, demonstrating how they can enhance the kinetics of charge transfer.
(viii) Zhang *et al.* (2022) are investigating the incorporation of 2D materials into hybrid substrates to improve stability and conductivity while encouraging effective water dissociation.
(ix) Xu *et al.* (2022) talk about advancements in cutting-edge characterization techniques, like cryo-electron microscopy, which offer a thorough understanding of the shape and structure of hybrid substrates at the nanoscale.
(x) Vivekanandhan *et al.* (2017) talk about the current state of research on the investigation of substitute carbon sources for the production of substrates, with a focus on renewable and sustainable feedstocks.
(xi) Wang *et al.* (2021b) draw attention to continuing studies that examine the possibility of doped carbon materials as catalytic materials, looking at the addition of heteroatoms to modify their electrical characteristics for improved water splitting.
(xii) Wang *et al.* (2017) talk about advances in theoretical modeling techniques that help with the creation of carbon-based substrates that have the best stability and reactivity.
(xiii) Chen *et al.* (2022) examine the current research being conducted on the creation of nanostructured substrates using controlled defect engineering, to improve catalytic performance and stability.
(xiv) Harish *et al.* (2023) emphasize advances in the synthesis of nanostructured substrates by the application of innovative templating agents, providing fine control over composition and morphology.
(xv) Dharmarajan *et al.* (2024) ongoing study investigates the integration of sophisticated templating methods, like directed self-assembly, to accurately regulate substrate nanostructure for effective water-splitting.
(xvi) Tabor *et al.* (2018) examine advancements in high-throughput screening techniques that expedite the identification of ideal nanostructured substrates via swift testing and examination.

A forward-looking viewpoint is presented in this section, where possible developments and current innovations in substrate selection are examined. This section seeks to inspire and direct future improvements in the dynamic field of water splitting for sustainable energy conversion by using lessons learned from real-world experiences found in research publications.

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4. CONCLUSION

To sum up, investigating various substrates for improved water splitting presents a viable path for the advancement of energy conversion and storage technologies. Researchers want to maximize the efficiency of water-splitting operations and help with industrial renewable energy production by customizing electrocatalysts to match individual needs. This review emphasizes the distinctive properties and uses of different catalysts while highlighting current advancements in substrate selection. This thorough review emphasizes the significance of substrate variability in affecting energy output, covering everything from basic concepts to cutting-edge techniques. Progress in this crucial area will be accelerated going ahead by tackling possible obstacles and exploring new research avenues, which will ultimately influence the development of sustainable energy production.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

6. REFERENCES

Ahn, J., Hong, S., Shim, Y. S., and Park, J. (2020). Electroplated functional materials with 3D nanostructures defined by advanced optical lithography and their emerging applications. *Applied Sciences*, *10*(24), 8780.

Aldhaher, A., Rabiee, N., and Iravani, S. (2023). Exploring the synergistic potential of MXene-MOF hybrid composites: A perspective on synthesis, properties, and applications. *Hybrid Advances*, *5,* 100131.

Aljibori, H. S., Alamiery, A., and Kadhum, A. A. H. (2023). Advances in corrosion protection coatings: A comprehensive review. *International Journal of Corrosion and Scale Inhibition*, *12*(4), 1476-1520.

Allangawi, A., Ayub, K., Gilani, M. A., Imran, M., and Mahmood, T. (2024). Transition metal loaded carbon penta-belt SACs for hydrogen and oxygen evolution reactions and identification of systematic DFT method to characterize the main interacting orbital for non-periodic system. *International Journal of Hydrogen Energy*, *53*, 989-998.

Al-Naggar, A. H., Shinde, N. M., Kim, J. S., and Mane, R. S. (2023). Water splitting performance of metal and non-metal-doped transition metal oxide electrocatalysts. *Coordination Chemistry Reviews*, *474*, 214864.

Alwin, S., and Sahaya Shajan, X. (2020). Aerogels: Promising nanostructured materials for energy conversion and storage applications. *Materials for Renewable and Sustainable Energy*, *9*(2), 7.

An, L., Feng, J., Zhang, Y., Wang, R., Liu, H., Wang, G. C., and Xi, P. (2019). Epitaxial heterogeneous interfaces on N-NiMoO4/NiS2 nanowires/nanosheets to boost hydrogen and oxygen production for overall water splitting. *Advanced Functional Materials*, *29*(1), 1805298.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Ansón-Casaos, A., Sanahuja-Parejo, O., Hernández-Ferrer, J., Benito, A. M., and Maser, W. K. (2020). Carbon nanotube film electrodes with acrylic additives: Blocking electrochemical charge transfer reactions. *Nanomaterials*, *10*(6), 1078.

Boamah, M. D., Lozier, E. H., Kim, J., Ohno, P. E., Walker, C. E., Miller III, T. F., and Geiger, F. M. (2019). Energy conversion via metal nanolayers. *Proceedings of the National Academy of Sciences*, *116*(33), 16210-16215.

Bosch, M., Zhang, M., and Zhou, H. C. (2014). Increasing the stability of metal-organic frameworks. *Advances in Chemistry*, *2014*(182327.10), 1155.

Boyes, W. K., Thornton, L. L., Al-Abed, S. R., Andersen, C. P., Bouchard, D. C., Burgess, R. M., and Zucker, R. M. (2017). A comprehensive framework for evaluating the environmental health and safety implications of engineered nanomaterials. *Critical Reviews in Toxicology*, *47*(9), 771-814.

Cao, L. M., Hu, Y. W., Tang, S. F., Iljin, A., Wang, J. W., Zhang, Z. M., and Lu, T. B. (2018). Fe-CoP electrocatalyst derived from a bimetallic Prussian Blue analogue for large-current-density oxygen evolution and overall water splitting. *Advanced Science*, *5*(10), 1800949.

Cazorla-Amorós, D. (2014). Grand challenges in carbon-based materials research. *Frontiers in Materials*, *1*, 6.

Chen, H., Jiang, D. E., Yang, Z., and Dai, S. (2022). Engineering nanostructured interfaces of hexagonal boron nitride-based materials for enhanced catalysis. *Accounts of Chemical Research*, *56*(1), 52-65.

Chen, J., Ren, B., Cui, H., and Wang, C. (2020). Constructing pure phase tungsten-based bimetallic carbide nanosheet as an efficient bifunctional electrocatalyst for overall water splitting. *Small*, *16*(23), 1907556.

Chen, P., Zhou, T., Zhang, M., Tong, Y., Zhong, C., Zhang, N., and Xie, Y. (2017a). 3D nitrogen-anion-decorated nickel sulfides for highly efficient overall water splitting. *Advanced Materials*, *29*(30), 1701584.

Chen, S., Takata, T., and Domen, K. (2017). Particulate photocatalysts for overall water splitting. *Nature Reviews Materials*, *2*(10), 1-17.

Cheng, G., Kou, T., Zhang, J., Si, C., Gao, H., and Zhang, Z. (2017). O22-/O-functionalized oxygen-deficient Co3O4 nanorods as high performance supercapacitor electrodes and electrocatalysts towards water splitting. *Nano Energy*, *38*, 155-166.

Cherevan, A. S., Nandan, S. P., Roger, I., Liu, R., Streb, C., and Eder, D. (2020). Polyoxometalates on functional substrates: concepts, synergies, and future perspectives. *Advanced Science*, *7*(8), 1903511.

Choi, H., Surendran, S., Sim, Y., Je, M., Janani, G., Choi, H., and Sim, U. (2022). Enhanced electrocatalytic full water-splitting reaction by interfacial electric field in 2D/2D heterojunction. *Chemical Engineering Journal*, *450*, 137789.

Concina, I., Ibupoto, Z. H., and Vomiero, A. (2017). Semiconducting metal oxide nanostructures for water splitting and photovoltaics. *Advanced Energy Materials*, *7*(23), 1700706.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Danish, M. S. S., Bhattacharya, A., Stepanova, D., Mikhaylov, A., Grilli, M. L., Khosravy, M., and Senjyu, T. (2020). A systematic review of metal oxide applications for energy and environmental sustainability. *Metals*, *10*(12), 1604.

Deng, S., Zhong, Y., Zeng, Y., Wang, Y., Wang, X., Lu, X., and Tu, J. (2018). Hollow TiO2@ Co9S8 core–branch arrays as bifunctional electrocatalysts for efficient oxygen/hydrogen production. *Advanced Science*, *5*(3), 1700772.

Dharmarajan, N. P., Vidyasagar, D., Yang, J. H., Talapaneni, S. N., Lee, J., Ramadass, K., and Vinu, A. (2024). Bio-inspired supramolecular self-assembled carbon nitride nanostructures for photocatalytic water splitting. *Advanced Materials*, *36*(2), 2306895.

Dong, C., Kou, T., Gao, H., Peng, Z., and Zhang, Z. (2018). Eutectic-derived mesoporous Ni-Fe-O nanowire network catalyzing oxygen evolution and overall water splitting. *Advanced Energy Materials*, *8*(5), 1701347.

Dou, Y., Zhang, W., and Kaiser, A. (2020). Electrospinning of metal–organic frameworks for energy and environmental applications. *Advanced Science*, *7*(3), 1902590.

Du, Y., Li, B., Xu, G., and Wang, L. (2023). Recent advances in interface engineering strategy for highly-efficient electrocatalytic water splitting. *InfoMat*, *5*(1), e12377.

Fanady, B., Song, W., Peng, R., Wu, T., and Ge, Z. (2020). Efficiency enhancement of organic solar cells enabled by interface engineering of sol-gel zinc oxide with an oxadiazole-based material. *Organic Electronics*, *76*, 105483.

Fang, M., Dong, G., Wei, R., and Ho, J. C. (2017). Hierarchical nanostructures: design for sustainable water splitting. *Advanced Energy Materials*, *7*(23), 1700559.

Fareza, A. R., Nugroho, F. A. A., Abdi, F. F., and Fauzia, V. (2022). Nanoscale metal oxides–2D materials heterostructures for photoelectrochemical water splitting—a review. *Journal of Materials Chemistry A*, *10*(16), 8656-8686.

Feng, L. L., Yu, G., Wu, Y., Li, G. D., Li, H., Sun, Y., and Zou, X. (2015). High-index faceted Ni3S2 nanosheet arrays as highly active and ultrastable electrocatalysts for water splitting. *Journal of the American Chemical Society*, *137*(44), 14023-14026.

Fester, J., García-Melchor, M., Walton, A. S., Bajdich, M., Li, Z., Lammich, L., and Lauritsen, J. V. (2017). Edge reactivity and water-assisted dissociation on cobalt oxide nanoislands. *Nature Communications*, *8*(1), 14169.

Genuzio, F., Menteş, T. O., Freindl, K., Spiridis, N., Korecki, J., and Locatelli, A. (2020). Chemistry-dependent magnetic properties at the FeNi oxide–metal interface. *Journal of Materials Chemistry C*, *8*(17), 5777-5785.

Grandell, L., and Höök, M. (2015). Assessing rare metal availability challenges for solar energy technologies. *Sustainability*, *7*(9), 11818-11837.

Groß, J., Kühlborn, J., and Opatz, T. (2020). Applications of xylochemistry from laboratory to industrial scale. *Green Chemistry*, *22*(14), 4411-4425.

Guo, Y., Tang, J., Wang, Z., Kang, Y. M., Bando, Y., and Yamauchi, Y. (2018). Elaborately assembled core-shell structured metal sulfides as a bifunctional catalyst for highly efficient electrochemical overall water splitting. *Nano Energy*, *47*, 494-502.

Han, N., Yang, K. R., Lu, Z., Li, Y., Xu, W., Gao, T., and Sun, X. (2018). Nitrogen-doped tungsten carbide nanoarray as an efficient bifunctional electrocatalyst for water splitting in acid. *Nature Communications*, *9*(1), 924.

Harish, V., Ansari, M. M., Tewari, D., Yadav, A. B., Sharma, N., Bawarig, S., and Barhoum, A. (2023). Cutting-edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review. *Journal of the Taiwan Institute of Chemical Engineers*, *149*, 105010.

Hegazy, H. H., Sana, S. S., Ramachandran, T., Kumar, Y. A., Kulurumotlakatla, D. K., Abd-Rabboh, H. S., and Kim, S. C. (2023). Covalent organic frameworks in supercapacitors: Unraveling the pros and cons for energy storage. *Journal of Energy Storage*, *74*, 109405.

Hisatomi, T., and Domen, K. (2019). Reaction systems for solar hydrogen production via water splitting with particulate semiconductor photocatalysts. *Nature Catalysis*, *2*(5), 387-399.

Hu, J., Al-Salihy, A., Zhang, B., Li, S., and Xu, P. (2022). Mastering the D-band center of iron-series metal-based electrocatalysts for enhanced electrocatalytic water splitting. *International Journal of Molecular Sciences*, *23*(23), 15405.

Huang, S., Meng, Y., He, S., Goswami, A., Wu, Q., Li, J., and Wu, M. (2017). N-, O-, and S-tridoped carbon-encapsulated Co9S8 nanomaterials: efficient bifunctional electrocatalysts for overall water splitting. *Advanced Functional Materials*, *27*(17), 1606585.

Huang, X., Yang, G., Li, S., Wang, H., Cao, Y., Peng, F., and Yu, H. (2022). Noble-metal-based high-entropy-alloy nanoparticles for electrocatalysis. *Journal of Energy Chemistry*, *68*, 721-751.

Huang, Y., Sun, Y., Zheng, X., Aoki, T., Pattengale, B., Huang, J., and Gu, J. (2019). Atomically engineering activation sites onto metallic 1T-MoS2 catalysts for enhanced electrochemical hydrogen evolution. *Nature Communications*, *10*(1), 982.

Hussain, M. A., Joseph, N., Kang, O., Cho, Y. H., Um, B. H., and Kim, J. W. (2016). Supported metal nanoparticles: their catalytic applications to selective alcohol oxidation. *Applied Chemistry for Engineering*, *27*(3), 227-238.

Iqbal, A. A., Sakib, N., Iqbal, A. P., and Nuruzzaman, D. M. (2020). Graphene-based nanocomposites and their fabrication, mechanical properties and applications. *Materialia*, *12*, 100815.

Jakhar, M., Kumar, A., Ahluwalia, P. K., Tankeshwar, K., and Pandey, R. (2022). Engineering 2D materials for photocatalytic water-splitting from a theoretical perspective. *Materials*, *15*(6), 2221.

Jayaseelan, S. S., Bhuvanendran, N., Xu, Q., and Su, H. (2020). Co3O4 nanoparticles decorated Polypyrrole/carbon nanocomposite as efficient bi-functional electrocatalyst for electrochemical water splitting. *International Journal of Hydrogen Energy*, *45*(7), 4587-4595.

Jeon, T. Y., Kim, D. J., Park, S. G., Kim, S. H., and Kim, D. H. (2016). Nanostructured plasmonic substrates for use as SERS sensors. *Nano Convergence*, *3*, 1-20.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Jiang, W. J., Tang, T., Zhang, Y., and Hu, J. S. (2020). Synergistic modulation of non-precious-metal electrocatalysts for advanced water splitting. *Accounts of Chemical Research*, *53*(6), 1111-1123.

Jiao, Y. Q., Yan, H. J., Tian, C. G., and Fu, H. G. (2022). Structure engineering and electronic modulation of transition metal interstitial compounds for electrocatalytic water splitting. *Accounts of Materials Research*, *4*(1), 42-56.

Jin, H., Wang, J., Su, D., Wei, Z., Pang, Z., and Wang, Y. (2015). In situ cobalt–cobalt oxide/N-doped carbon hybrids as superior bifunctional electrocatalysts for hydrogen and oxygen evolution. *Journal of the American Chemical Society*, *137*(7), 2688-2694.

Jin, Y., Wang, H., Li, J., Yue, X., Han, Y., Shen, P. K., and Cui, Y. (2016). Porous MoO2 nanosheets as non-noble bifunctional electrocatalysts for overall water splitting. *Advanced Materials*, *28*(19), 3785-3790.

Kawasaki, S., Takahashi, R., Yamamoto, T., Kobayashi, M., Kumigashira, H., Yoshinobu, J., and Lippmaa, M. (2016). Photoelectrochemical water splitting enhanced by self-assembled metal nanopillars embedded in an oxide semiconductor photoelectrode. *Nature Communications*, *7*(1), 11818.

Kim, M., Kwon, B. H., Joo, C. W., Cho, M. S., Jang, H., Kim, Y. J., and Jung, Y. S. (2022). Metal oxide charge transfer complex for effective energy band tailoring in multilayer optoelectronics. *Nature Communications*, *13*(1), 75.

Kleinschmidt, D., Fernandes, M. S., Mork, M., Meyer, A. A., Krischel, J., Anakhov, M. V., and Pich, A. (2020). Enhanced catalyst performance through compartmentalization exemplified by colloidal L-proline modified microgel catalysts. *Journal of Colloid and Interface Science*, *559*, 76-87.

Kou, Z., Zhang, L., Ma, Y., Liu, X., Zang, W., Zhang, J., and Wang, J. (2019). 2D carbide nanomeshes and their assembling into 3D microflowers for efficient water splitting. *Applied Catalysis B: Environmental*, *243*, 678-685.

Kundu, S., Bramhaiah, K., and Bhattacharyya, S. (2020). Carbon-based nanomaterials: in the quest of alternative metal-free photocatalysts for solar water splitting. *Nanoscale Advances*, *2*(11), 5130-5151.

Lee, J. S. (2012). Photoelectrochemical water splitting for solar hydrogen production over semiconductor nanostructures. *Rapid Communication in Photoscience: RCP*, *1*(2), 39-39.

Lei, C., Wang, Y., Hou, Y., Liu, P., Yang, J., Zhang, T., and Feng, X. (2019). Efficient alkaline hydrogen evolution on atomically dispersed Ni–N x Species anchored porous carbon with embedded Ni nanoparticles by accelerating water dissociation kinetics. *Energy and Environmental Science*, *12*(1), 149-156.

Li, F., and Xue, M. (2016). Two-dimensional transition metal dichalcogenides for electrocatalytic energy conversion applications. *Two-dimensional Materials-Synthesis, Characterization and Potential Applications*, 64-84.

Li, J., Wang, Y., Zhou, T., Zhang, H., Sun, X., Tang, J., and Zheng, G. (2015). Nanoparticle superlattices as efficient bifunctional electrocatalysts for water splitting. *Journal of the American Chemical Society*, *137*(45), 14305-14312.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Li, M., Zhu, Y., Wang, H., Wang, C., Pinna, N., and Lu, X. (2019). Ni strongly coupled with Mo2C encapsulated in nitrogen-doped carbon nanofibers as robust bifunctional catalyst for overall water splitting. *Advanced Energy Materials*, *9*(10), 1803185.

Li, X., Hao, X., Abudula, A., and Guan, G. (2016). Nanostructured catalysts for electrochemical water splitting: current state and prospects. *Journal of Materials Chemistry A*, *4*(31), 11973-12000.

Li, X., Liu, L., Ren, X., Gao, J., Huang, Y., and Liu, B. (2020). Microenvironment modulation of single-atom catalysts and their roles in electrochemical energy conversion. *Science Advances*, *6*(39), eabb6833.

Li, Y., Zhang, H., Jiang, M., Zhang, Q., He, P., and Sun, X. (2017). 3D self-supported Fe-doped Ni2P nanosheet arrays as bifunctional catalysts for overall water splitting. *Advanced Functional Materials*, *27*(37), 1702513.

Liang, Q., Jin, H., Wang, Z., Xiong, Y., Yuan, S., Zeng, X., and Mu, S. (2019). Metal-organic frameworks derived reverse-encapsulation Co-NC@ Mo2C complex for efficient overall water splitting. *Nano Energy*, *57*, 746-752.

Liao, W., Wang, S., Su, H., and Zhang, Y. (2023). Application of in situ/operando characterization techniques in heterostructure catalysts toward water electrolysis. *Nano Research*, *16*(2), 1984-1991.

Lin, J., Wang, P., Wang, H., Li, C., Si, X., Qi, J., and Feng, J. (2019). Defect-rich heterogeneous MoS2/NiS2 nanosheets electrocatalysts for efficient overall water splitting. *Advanced Science*, *6*(14), 1900246.

Liu, J., Wagan, S., Dávila Morris, M., Taylor, J., and White, R. J. (2014a). Achieving reproducible performance of electrochemical, folding aptamer-based sensors on microelectrodes: challenges and prospects. *Analytical Chemistry*, *86*(22), 11417-11424.

Liu, Y., Jiang, S., Li, S., Zhou, L., Li, Z., Li, J., and Shao, M. (2019). Interface engineering of (Ni, Fe) S2@ MoS2 heterostructures for synergetic electrochemical water splitting. *Applied Catalysis B: Environmental*, *247*, 107-114.

Liu, Y., Wang, Y. M., Yakobson, B. I., and Wood, B. C. (2014b). Assessing carbon-based anodes for lithium-ion batteries: A universal description of charge-transfer binding. *Physical Review Letters*, *113*(2), 028304.

Liu, Z., Zhao, Z., Zhang, W., Huang, Y., Liu, Y., Wu, D., and Chou, S. (2022). Toward high-performance lithium-oxygen batteries with cobalt-based transition metal oxide catalysts: Advanced strategies and mechanical insights. *InfoMat*, *4*(4), e12260.

Loera-Serna, S., and Ortiz, E. (2016). Catalytic applications of metal-organic frameworks. *Luis N, Advanced Catalytic Materials-Photocatalysis and Other Current Trends, IntechOpen*, *2016,* 95-122.

Luneau, M., Guan, E., Chen, W., Foucher, A. C., Marcella, N., Shirman, T., and Friend, C. M. (2020). Enhancing catalytic performance of dilute metal alloy nanomaterials. *Communications Chemistry*, *3*(1), 46.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Luo, X., Ji, P., Wang, P., Cheng, R., Chen, D., Lin, C., and Mu, S. (2020). Interface engineering of hierarchical branched Mo-doped Ni3S2/NixPy hollow heterostructure nanorods for efficient overall water splitting. *Advanced Energy Materials*, *10*(17), 1903891.

Masood ul Hasan, I., Peng, L., Mao, J., He, R., Wang, Y., Fu, J., and Qiao, J. (2021). Carbon-based metal-free catalysts for electrochemical CO2 reduction: Activity, selectivity, and stability. *Carbon Energy*, *3*(1), 24-49.

Mayer, M. T., Lin, Y., Yuan, G., and Wang, D. (2013). Forming heterojunctions at the nanoscale for improved photoelectrochemical water splitting by semiconductor materials: Case studies on hematite. *Accounts of Chemical Research*, *46*(7), 1558-1566.

Melkiyur, I., Rathinam, Y., Kumar, P. S., Sankaiya, A., Pitchaiya, S., Ganesan, R., and Velauthapillai, D. (2023). A comprehensive review on novel quaternary metal oxide and sulphide electrode materials for supercapacitor: Origin, fundamentals, present perspectives and future aspects. *Renewable and Sustainable Energy Reviews*, *173*, 113106.

Meyer, K., Ranocchiari, M., and van Bokhoven, J. A. (2015). Metal organic frameworks for photo-catalytic water splitting. *Energy and Environmental Science*, *8*(7), 1923-1937.

Mowbray, D. J., Martinez, J. I., Calle-Vallejo, F., Rossmeisl, J., Thygesen, K. S., Jacobsen, K. W., and Nørskov, J. K. (2011). Trends in metal oxide stability for nanorods, nanotubes, and surfaces. *The Journal of Physical Chemistry C*, *115*(5), 2244-2252.

Naghavi, S. S., Emery, A. A., Hansen, H. A., Zhou, F., Ozolins, V., and Wolverton, C. (2017). Giant onsite electronic entropy enhances the performance of ceria for water splitting. *Nature Communications*, *8*(1), 285.

Nasir, S., Hussein, M. Z., Zainal, Z., Yusof, N. A., Zobir, S. A. M., and Alibe, I. M. (2019). Potential valorization of by-product materials from oil palm: A review of alternative and sustainable carbon sources for carbon-based nanomaterials synthesis. *BioResources*, *14*(1), 2352-2388.

Nasrollahzadeh, M., Sajjadi, M., Iravani, S., and Varma, R. S. (2021). Carbon-based sustainable nanomaterials for water treatment: State-of-art and future perspectives. *Chemosphere*, *263*, 128005.

Nemiwal, M., Gosu, V., Zhang, T. C., and Kumar, D. (2021a). Metal organic frameworks as electrocatalysts: Hydrogen evolution reactions and overall water splitting. *International Journal of Hydrogen Energy*, *46*(17), 10216-10238.

Nemiwal, M., Zhang, T. C., and Kumar, D. (2021b). Graphene-based electrocatalysts: Hydrogen evolution reactions and overall water splitting. *International Journal of Hydrogen Energy*, *46*(41), 21401-21418.

Pellegrino, P., Bramanti, A. P., Farella, I., Cascione, M., De Matteis, V., Della Torre, A., and Rinaldi, R. (2022). Pulse-atomic force lithography: A powerful nanofabrication technique to fabricate constant and varying-depth nanostructures. *Nanomaterials*, *12*(6), 991.

Peng, J., He, Y., Zhou, C., Su, S., and Lai, B. (2021). The carbon nanotubes-based materials and their applications for organic pollutant removal: A critical review. *Chinese Chemical Letters*, *32*(5), 1626-1636.

Peng, S., Gong, F., Li, L., Yu, D., Ji, D., Zhang, T., and Ramakrishna, S. (2018). Necklace-like multishelled hollow spinel oxides with oxygen vacancies for efficient water electrolysis. *Journal of the American Chemical Society*, *140*(42), 13644-13653.

Qiu, B., Cai, L., Zhang, N., Tao, X., and Chai, Y. (2020). A ternary dumbbell structure with spatially separated catalytic sites for photocatalytic overall water splitting. *Advanced Science*, *7*(17), 1903568.

Raza, A., Zhang, X., Ali, S., Cao, C., Rafi, A. A., and Li, G. (2022). Photoelectrochemical energy conversion over 2D materials. *Photochem*, *2*(2), 272-298.

Reza, M. S., Ahmad, N. B. H., Afroze, S., Taweekun, J., Sharifpur, M., and Azad, A. K. (2023). Hydrogen Production from Water Splitting through Photocatalytic Activity of Carbon-Based Materials. *Chemical Engineering and Technology*, *46*(3), 420-434.

Rocío-Bautista, P., Taima-Mancera, I., Pasán, J., and Pino, V. (2019). Metal-organic frameworks in green analytical chemistry. *Separations*, *6*(3), 33.

Roger, I., Shipman, M. A., and Symes, M. D. (2017). Earth-abundant catalysts for electrochemical and photoelectrochemical water splitting. *Nature Reviews Chemistry*, *1*(1), 1-13.

Ronge, E., Cottre, T., Welter, K., Smirnov, V., Ottinger, N. J., Finger, F., ... and Jooss, C. (2020). Stability and degradation mechanismof si-based photocathodes for water splitting with ultrathin TiO2 protection layer. *Zeitschrift für Physikalische Chemie*, *234*(6), 1171-1184.

Safdari, M., and Al-Haik, M. S. (2018). A review on polymeric nanocomposites: effect of hybridization and synergy on electrical properties. *Carbon-Based Polymer Nanocomposites for Environmental and Energy Applications*, *2018,* 113-146.

Sahoo, D. P., Das, K. K., Mansingh, S., Sultana, S., and Parida, K. (2022). Recent progress in first row transition metal Layered double hydroxide (LDH) based electrocatalysts towards water splitting: A review with insights on synthesis. *Coordination Chemistry Reviews*, *469*, 214666.

Sahoo, P. K., Bisoi, S. R., Huang, Y. J., Tsai, D. S., and Lee, C. P. (2021). 2D-layered non-precious electrocatalysts for hydrogen evolution reaction: Fundamentals to applications. *Catalysts*, *11*(6), 689.

Shah, S. S. A., Javed, M. S., Najam, T., Molochas, C., Khan, N. A., Nazir, M. A., and Bao, S. J. (2022). Metal oxides for the electrocatalytic reduction of carbon dioxide: Mechanism of active sites, composites, interface and defect engineering strategies. *Coordination Chemistry Reviews*, *471*, 214716.

Shen, S., Sun, K., Zhang, H., and Liang, Y. (2014). Advanced catalysis and nanostructure design for solar energy conversion. *Advances in Condensed Matter Physics*, *2014*, 1-4.

Shkodenko, L., Kassirov, I., and Koshel, E. (2020). Metal oxide nanoparticles against bacterial biofilms: Perspectives and limitations. *Microorganisms*, *8*(10), 1545.

Stoica, I., Sava, I., Bulai, G., Stoian, G., Strat, M., Gurlui, S., and Oprisan, B. (2020). Development and morphological characterization of novel polyimide/metal nano hybrid materials. *Materiale Plastice*, *57*(2), 94-103.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Sun, H., Yan, Z., Liu, F., Xu, W., Cheng, F., and Chen, J. (2020). Self-supported transition-metal-based electrocatalysts for hydrogen and oxygen evolution. *Advanced Materials*, *32*(3), 1806326.

Sun, L., Ji, X., Zhou, Y., Li, H., Zhai, W., Chen, B., ... and Wang, T. (2023). An overview of hydrogen production from Al-based materials. *Nanotechnology Reviews*, *12*(1), 20220521.

Sun, L., Luo, Q., Dai, Z., and Ma, F. (2021a). Material libraries for electrocatalytic overall water splitting. *Coordination Chemistry Reviews*, *444*, 214049.

Sun, X., Bao, J., Li, K., Argyle, M. D., Tan, G., Adidharma, H., and Ning, P. (2021b). Advance in using plasma technology for modification or fabrication of carbon-based materials and their applications in environmental, material, and energy fields. *Advanced Functional Materials*, *31*(7), 2006287.

Swesi, A. T., Masud, J., Liyanage, W. P., Umapathi, S., Bohannan, E., Medvedeva, J., and Nath, M. (2017). Textured NiSe2 film: bifunctional electrocatalyst for full water splitting at remarkably low overpotential with high energy efficiency. *Scientific Reports*, *7*(1), 2401.

Tabakaev, R. B., Astafyev, A. V., Kazakov, A. V., and Zavorin, A. S. (2015). Low-temperature catalytic conversion of carbonaceous materials. *MATEC Web of Conferences. Vol. 23: Heat and Mass Transfer in the Thermal Control System of Technical and Technological Energy Equipment.—Les Ulis, 2015, 23*, 10394.

Tabor, D. P., Roch, L. M., Saikin, S. K., Kreisbeck, C., Sheberla, D., Montoya, J. H., and Aspuru-Guzik, A. (2018). Accelerating the discovery of materials for clean energy in the era of smart automation. *Nature Reviews Materials*, *3*(5), 5-20.

Tachibana, Y., Vayssieres, L., and Durrant, J. R. (2012). Artificial photosynthesis for solar water-splitting. *Nature Photonics*, *6*(8), 511-518.

Tachikawa, T., and Majima, T. (2014). Metal oxide mesocrystals with tailored structures and properties for energy conversion and storage applications. *NPG Asia Materials*, *6*(5), e100-e100.

Tamayo, L., Palza, H., Bejarano, J., and Zapata, P. A. (2019). Polymer composites with metal nanoparticles: synthesis, properties, and applications. *Polymer Composites with Functionalized Nanoparticles*, *2019*,249-286.

Tang, D., Mabayoje, O., Lai, Y., Liu, Y., and Mullins, C. B. (2017a). Enhanced photoelectrochemical performance of porous Bi2MoO6 photoanode by an electrochemical treatment. *Journal of The Electrochemical Society*, *164*(6), H299.

Tang, M. H., Chakthranont, P., and Jaramillo, T. F. (2017). Top-down fabrication of fluorine-doped tin oxide nanopillar substrates for solar water splitting. *RSC Advances*, *7*(45), 28350-28357.

Tang, Y. J., Zheng, H., Wang, Y., Zhang, W., and Zhou, K. (2021). Laser-induced annealing of metal–organic frameworks on conductive substrates for electrochemical water splitting. *Advanced Functional Materials*, *31*(31), 2102648.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Tao, L., Wang, Y., Zou, Y., Zhang, N., Zhang, Y., Wu, Y., and Wang, S. (2020). Charge transfer modulated activity of carbon-based electrocatalysts. *Advanced Energy Materials*, *10*(11), 1901227.

Toma, F. M., Sartorel, A., Carraro, M., Bonchio, M., and Prato, M. (2011). Dendron-functionalized multiwalled carbon nanotubes incorporating polyoxometalates for water-splitting catalysis. *Pure and Applied Chemistry*, *83*(8), 1529-1542.

Toshima, N. (2013). Metal nanoparticles for energy conversion. *Pure and Applied Chemistry*, *85*(2), 437-451.

Uwaya, G. E., and Fayemi, O. E. (2021). Enhanced electrocatalytic detection of choline based on CNTs and metal oxide nanomaterials. *Molecules*, *26*(21), 6512.

Vanka, S., Zeng, G., Deutsch, T. G., Toma, F. M., and Mi, Z. (2022). Long-term stability metrics of photoelectrochemical water splitting. *Frontiers in Energy Research*, *10*, 840140.

Venditti, I. (2022). Metal nanoparticles–polymers hybrid materials I. *Polymers*, *14*(15), 3117.

Vivekanandhan, S., Schreiber, M., Muthuramkumar, S., Misra, M., and Mohanty, A. K. (2017). Carbon nanotubes from renewable feedstocks: A move toward sustainable nanofabrication. *Journal of Applied Polymer Science*, *134*(4), 1-15.

Wang, B., Iocozzia, J., Zhang, M., Ye, M., Yan, S., Jin, H., and Lin, Z. (2019). The charge carrier dynamics, efficiency and stability of two-dimensional material-based perovskite solar cells. *Chemical Society Reviews*, *48*(18), 4854-4891.

Wang, H., Cao, Y., Sun, C., Zou, G., Huang, J., Kuai, X., and Gao, L. (2017). Strongly coupled molybdenum carbide on carbon sheets as a bifunctional electrocatalyst for overall water splitting. *ChemSusChem*, *10*(18), 3540-3546.

Wang, H., Chen, Z. N., Wu, D., Cao, M., Sun, F., Zhang, H., and Cao, R. (2021a). Significantly enhanced overall water splitting performance by partial oxidation of Ir through Au modification in core–shell alloy structure. *Journal of the American Chemical Society*, *143*(12), 4639-4645.

Wang, H., Lee, H. W., Deng, Y., Lu, Z., Hsu, P. C., Liu, Y., and Cui, Y. (2015). Bifunctional non-noble metal oxide nanoparticle electrocatalysts through lithium-induced conversion for overall water splitting. *Nature Communications*, *6*(1), 7261.

Wang, J., Liao, T., Wei, Z., Sun, J., Guo, J., and Sun, Z. (2021b). Heteroatom-doping of non-noble metal-based catalysts for electrocatalytic hydrogen evolution: An electronic structure tuning strategy. *Small Methods*, *5*(4), 2000988.

Wang, S., Xu, L., and Lu, W. (2018). Synergistic effect: Hierarchical Ni3S2@ Co (OH) 2 heterostructure as efficient bifunctional electrocatalyst for overall water splitting. *Applied Surface Science*, *457*, 156-163.

Wang, X. H., Ling, Y., Wu, B., Li, B. L., Li, X. L., Lei, J. L., ... and Luo, H. Q. (2021c). Doping modification, defects construction, and surface engineering: Design of cost-effective high-performance electrocatalysts and their application in alkaline seawater splitting. *Nano Energy*, *87*, 106160.

Wang, X., Vasileff, A., Jiao, Y., Zheng, Y., and Qiao, S. Z. (2019). Electronic and structural engineering of carbon-based metal-free electrocatalysts for water splitting. *Advanced Materials*, *31*(13), 1803625.

Wu, R., Xiao, B., Gao, Q., Zheng, Y. R., Zheng, X. S., Zhu, J. F., and Yu, S. H. (2018). A janus nickel cobalt phosphide catalyst for high-efficiency neutral-pH water splitting. *Angewandte Chemie*, *130*(47), 15671-15675.

Wu, Y., Li, G. D., Liu, Y., Yang, L., Lian, X., Asefa, T., and Zou, X. (2016). Overall water splitting catalyzed efficiently by an ultrathin nanosheet-built, hollow Ni3S2-based electrocatalyst. *Advanced Functional Materials*, *26*(27), 4839-4847.

Wu, Y., Tao, X., Qing, Y., Xu, H., Yang, F., Luo, S., and Lu, X. (2019). Cr-Doped FeNi–P nanoparticles encapsulated into N-doped carbon nanotube as a robust bifunctional catalyst for efficient overall water splitting. *Advanced Materials*, *31*(15), 1900178.

Xu, H., Shang, H., Wang, C., and Du, Y. (2020). Surface and interface engineering of noble-metal-free electrocatalysts for efficient overall water splitting. *Coordination Chemistry Reviews*, *418*, 213374.

Xu, S., Chansai, S., Stere, C., Inceesungvorn, B., Goguet, A., Wangkawong, K., ... and Fan, X. (2019). Sustaining metal–organic frameworks for water–gas shift catalysis by non-thermal plasma. *Nature Catalysis*, *2*(2), 142-148.

Xu, X., Li, W., Wang, X., and Dou, S. X. (2011). Superconducting properties of graphene doped magnesium diboride. *Applications of High-Tc Superconductivity*, 201-218.

Xu, Y., Dong, K., Jie, Y., Adelhelm, P., Chen, Y., Xu, L., Yu, Z. J. A. E. M. (2022). Promoting mechanistic understanding of lithium deposition and solid-electrolyte interphase (SEI) formation using advanced characterization and simulation methods: recent progress, limitations, and future perspectives. 12(19), 2200398.

Xu, Y., Fan, K., Zou, Y., Fu, H., Dong, M., Dou, Y., Al-Mamun, M. J. N. (2021). Rational design of metal oxide catalysts for electrocatalytic water splitting. 13(48), 20324-20353.

Xu, Z., Wang, H., Wen, Y., Li, W., Sun, C., He, Y., and Zou, Z. (2018). Balancing catalytic activity and interface energetics of electrocatalyst-coated photoanodes for photoelectrochemical water splitting. *ACS Applied Materials and Interfaces*, *10*(4), 3624-3633.

Xue, Y., Chen, S., Yu, J., Bunes, B. R., Xue, Z., Xu, J., and Zang, L. (2020). Nanostructured conducting polymers and their composites: Synthesis methodologies, morphologies and applications. *Journal of Materials Chemistry C*, *8*(30), 10136-10159.

Xue, Z. H., Su, H., Yu, Q. Y., Zhang, B., Wang, H. H., Li, X. H., and Chen, J. S. (2017). Janus Co/CoP nanoparticles as efficient Mott–Schottky electrocatalysts for overall water splitting in wide pH range. *Advanced Energy Materials*, *7*(12), 1602355.

Yan, L., Zhang, B., Zhu, J., Li, Y., Tsiakaras, P., and Shen, P. K. (2020a). Electronic modulation of cobalt phosphide nanosheet arrays via copper doping for highly efficient neutral-pH overall water splitting. *Applied Catalysis B: Environmental*, *265*, 118555.

Yan, Z., Liu, H., Hao, Z., Yu, M., Chen, X., and Chen, J. (2020b). Electrodeposition of (hydro) oxides for an oxygen evolution electrode. *Chemical Science*, *11*(39), 10614-10625.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236

Yang, L., Liu, R., and Jiao, L. (2020). Electronic redistribution: construction and modulation of interface engineering on CoP for enhancing overall water splitting. *Advanced Functional Materials*, *30*(14), 1909618.

Yang, Q., Xu, Q., and Jiang, H.-L. (2017). Metal–organic frameworks meet metal nanoparticles: synergistic effect for enhanced catalysis. *Chemical Society Reviews*, *46*(15), 4774-4808.

Yang, Y., Xiong, Y., Zeng, R., Lu, X., Krumov, M., Huang, X., and Abruña, H. D. (2021). Operando methods in electrocatalysis. *ACS Catalysis*, *11*(3), 1136-1178.

Yang, Y., Yao, H., Yu, Z., Islam, S. M., He, H., Yuan, M., and Kanatzidis, M. G. (2019). Hierarchical nanoassembly of MoS2/Co9S8/Ni3S2/Ni as a highly efficient electrocatalyst for overall water splitting in a wide pH range. *Journal of the American Chemical Society*, *141*(26), 10417-10430.

You, B., Liu, X., Hu, G., Gul, S., Yano, J., Jiang, D. E., and Sun, Y. (2017). Universal surface engineering of transition metals for superior electrocatalytic hydrogen evolution in neutral water. *Journal of the American Chemical Society*, *139*(35), 12283-12290.

Yu, F., Zhou, H., Huang, Y., Sun, J., Qin, F., Bao, J., and Ren, Z. (2018). High-performance bifunctional porous non-noble metal phosphide catalyst for overall water splitting. *Nature Communications*, *9*(1), 2551.

Yuan, C. Z., Hui, K. S., Yin, H., Zhu, S., Zhang, J., Wu, X. L., and Hui, K. N. (2021). Regulating intrinsic electronic structures of transition-metal-based catalysts and the potential applications for electrocatalytic water splitting. *ACS Materials Letters*, *3*(6), 752-780.

Zhang, F., Yu, L., Wu, L., Luo, D., and Ren, Z. (2021). Rational design of oxygen evolution reaction catalysts for seawater electrolysis. *Trends in Chemistry*, *3*(6), 485-498.

Zhang, J., Wang, T., Pohl, D., Rellinghaus, B., Dong, R., Liu, S., and Feng, X. (2016a). Interface engineering of MoS2/Ni3S2 heterostructures for highly enhanced electrochemical overall-water-splitting activity. *Angewandte Chemie*, *128*(23), 6814-6819.

Zhang, J., Xia, Z., and Dai, L. (2015). Carbon-based electrocatalysts for advanced energy conversion and storage. *Science Advances*, *1*(7), e1500564.

Zhang, L., Cui, P., Yang, H., Chen, J., Xiao, F., Guo, Y., and Liu, B. (2016b). Metal–organic frameworks as promising photosensitizers for photoelectrochemical water splitting. *Advanced Science*, *3*(1), 1500243.

Zhang, S., Gao, G., Hao, J., Wang, M., Zhu, H., Lu, S., and Zhao, Y. (2019). Low-electronegativity vanadium substitution in cobalt carbide induced enhanced electron transfer for efficient overall water splitting. *ACS Applied Materials and Interfaces*, *11*(46), 43261-43269.

Zhang, X., Dong, C. L., Wang, Y., Chen, J., Arul, K. T., Diao, Z., and Shen, S. (2020). Regulating crystal structure and atomic arrangement in single-component metal oxides through electrochemical conversion for efficient overall water splitting. *ACS Applied Materials and Interfaces*, *12*(51), 57038-57046.

Zhang, X., Fang, X., Zhu, K., Yuan, W., Jiang, T., Xue, H., and Tian, J. (2022). Fe-doping induced electronic structure reconstruction in Ni-based metal-organic framework for improved energy-saving hydrogen production via urea degradation. *Journal of Power Sources*, *520*, 230882.

Zhong, Y., Xia, X., Shi, F., Zhan, J., Tu, J., and Fan, H. J. (2016). Transition metal carbides and nitrides in energy storage and conversion. *Advanced Science*, *3*(5), 1500286.

Zhou, Y. N., Zhu, Y. R., Chen, X. Y., Dong, B., Li, Q. Z., and Chai, Y. M. (2021). Carbon–based transition metal sulfides/selenides nanostructures for electrocatalytic water splitting. *Journal of Alloys and Compounds*, *852*, 156810.

Zou, X., and Zhang, Y. (2015). Noble metal-free hydrogen evolution catalysts for water splitting. *Chemical Society Reviews*, *44*(15), 5148-5180.

辻豪, 渡邊一正, 實石陽一, 鈴木宏隆, 岩元和敏, 吉田章一郎, and 妹尾学. (1999). バイポーラ膜中の水の電離に対する金属酸化物水和物の触媒効果. *日本化学会誌 (化学と工業化学)*, *1999*(7), 441-444.

DOI:
p-ISSN: 2828-3309X e-ISSN: 2828-3236