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Recent Analytical Techniques for Encrustation in Ureteral Stents: A Review

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Abstract

The purpose of this review is to explore the issue of ureteral stent encrustation, a common complication following stent placement, and to examine recent advancements in the literature regarding its prevention and management. This review synthesizes peer-reviewed studies and methods for analyzing and evaluating ureteral stent encrustation, as well as emerging technologies aimed at addressing the challenges associated with this issue. The focus is on understanding the mechanisms behind encrustation, which can involve crystalline biofilms alone or in conjunction with bacterial biofilms. Recent research highlights the significant challenges posed by stent encrustation, including its impact on patient outcomes and the potential for serious complications. Various analytical methods for evaluating encrustation, along with advancements in stent design and coatings, have been explored to mitigate these issues. Given the growing concerns about complications from ureteral stent placement, particularly encrustation, continued research into innovative stent technologies and effective methods for preventing and managing encrustation is critical to improving patient care and outcomes.

Keywords: Ureteral Stent; Encrustation; Biomaterials; qPCR; SEM ;FTIR..

1.Introduction

A urethral stent is often used to avoid blockage. Relieves pain in cases of severe blockage. Prepare the patient for endoscopic stone treatment. or placing a stent at the ureteral junction after a kidney transplant to prevent blockage due to edema in the early postoperative period [1]. Urinary tract infections and irritation, which It is the most prevalent infection in hospitals. These issues include the development of microbial biofilms and the encapsulation of biomaterials with urinary tract components crystallizing on the surface [2]. It is an intricate network of microorganisms encased in a matrix of extracellular polymers [3]. Critical elements for encapsulation and growth The goal of both past and present research has been to create coil coverings or materials that can stop this process. However, because bacterial adhesion is a complicated process, this is hard to confirm. Different adhesion processes are used by different types of organisms. This makes finding a therapy that works for everyone difficult. Urine components can also change surface coatings' biological activity. Consequently, the anti-adhesion qualities are diminished [4]. In spite of these obstacles, However, several technologies have been developed. To lessen the strain of stent insertion The build-up of mineral crystals on the renal stent's surface and inside its lumen is referred to as encapsulation. Serious difficulties may result from this [5]. For long-term inhabitants or coils that have been neglected or stowed, this is particularly problematic. Up to 13% of all cases are affected by this [6]. When the coil is clogged It loses calcium, brittleness, and tensile strength. This increases the risk of ureteral fracture or perforation during removal. Additionally, crystal deposits may prevent drainage through the stent lumen and interact with the urethral lining. causing injury to the urethra Urethral stents [7]. Long-term wear is also associated with a higher risk of chronic kidney disease. and more hospital admissions due to urinary tract infections or sepsis after stent removal [8]. Researchers in the field of urology have used various methods. To evaluate these stents and prevent biofilm formation in new ways. and has a good trend to better understand the basic mechanisms of encapsulation and biofilm formation. Several studies have looked at patients with ureteral stents and analyzed their symptoms. Period [9], The relationship between bacterial colonization characteristics and rates was studied in a study by Betschart et al., patients with ureteral stents were monitored for symptoms and biofilm presence [10]. The prospective observational study found no significant correlation between biofilm mass and stent-related symptoms. However, patients with long-term stents had a 36% higher biofilm mass compared to those with shorter stent durations. This suggested that biofilms were not the primary cause of symptoms associated with long-term stenting. Additionally, Betschart et al. found no significant link between biofilm mass and Ureteral Stent Symptoms Questionnaire scores. Still, they noted correlations between biofilm mass and hematuria and bacterial count and pain scores. These findings suggest that while biofilms can worsen lower urinary tract symptoms, they are not the main cause of stent-related issues in short-term use. Furthermore, Cottone et al. [11] explored HEMA-coated Pellethane stents, finding them resistant to encrustation and highlighting their potential for medical applications. In their study, we compared encrustation formation on HEMA-coated Pellethane stents with various commercially available polymer-based stents, each featuring different surface chemistries designed to reduce urinary element deposition The stents were evaluated using an in vitro batch flow model. and

tested with two synthetic urine solutions: one solution simulated the formation of calcium oxalate; and other conditions that favor stone infection such as struvite and hydroxyapatite. Toprak et al. [12] investigated the effect of the duration of stent placement on the risk of clinical infection in patients who received a ureteral stent after kidney stone treatment. Participants were divided into two groups: one had the stent removed at 15 days and the other at 30 days. Preoperative and postoperative urine cultures were analyzed. along with microbiological examination of the stent after surgery The study found no direct link between bacterial colonization and symptomatic infection. However, prolonged stent placement was associated with bacterial growth on the stent. It was also found that urine cultures did not accurately reflect stent colonization. This indicates the need for a comprehensive approach that includes careful management of urine cultures, the use of stents, and prophylaxis to reduce the risk of infection. Shabina et al. [13] noted that Bacterial colonization on the ureteral stents increased significantly over time, from 7 days to 120 days. Their findings suggest that prolonged stent placement allows bacteria to build strong communities and Can develop biofilms This indicates a clear relationship between stent duration and bacterial growth [14].

2.Material and Methods

2.1 Encrustations

Urethral stent encapsulation is a complex process that involves the assembly of microbial biofilms and organic and inorganic deposits. Biofilms consist of a colony of microbial cells embedded in a self-produced extracellular polymeric material. Encapsulation occurs when metal from urine collects on the stent. Causes the accumulation of crystal deposits. Important risk factors for stent encapsulation include the duration of stent placement. Bacterial colonization Characteristics of each patient and the physical properties of the covered coils [15]. These problems can have a significant impact on the patient's quality of life. And create a significant financial burden. The same is true for the treatment or removal of covered coils [16] [17]. Additional procedures may be necessary. Encapsulation generally involves the accumulation of crystals on the inner and outer surfaces of the urethral stent [18]. This can lead to serious complications. This is especially true when coils are prolonged or forgotten. Severe encapsulation, which occurs in up to 13% of cases, can reduce the tensile strength of the coil [19]. And increases the risk of breakage during removal. It may also result in loss of kidney function due to urethral damage, perforation, urinary tract infection (UTI), or chronic obstruction of stent removal due to crystal deposits [18][20][21].

In terms of classification, proposed a visual grading system called Visual Grading of ureteral Encrusted Stents (V-GUES), which ranges from A to D according to the severity of encrusted stents. And V-GUES improves the efficiency of patient treatment. With the coils wrapped in the first place [22] … it was worrisome. However, the FECal (forgotten, wrapped, calcified) grading system developed by Acosta-Miranda is becoming more widely accepted to evaluate the severity of stent encapsulation. According to the studies of Gunner et al. and Hu et al. (2024) [23], this system classifies encapsulation from minimal involvement. (in the distal part of the stent, such as the bladder) to severe cases where both parts are close The end part (renal pelvis) and the distal part (bladder) of the stent are complete. Decorated with crystals. A similar grading system called the KUB system is also used in clinical practice. Long-lasting ureteral stents are associated with an increased incidence of surface stones. This is mainly due to the development of a modified urinary film on the stent surface, which occurs when proteins in the urine adsorb to the stent material. This is a process that is often aggravated by electrostatic interactions. It is recommended to increase the hydrophilicity of the stent surface to reduce encapsulation. Because it can reduce friction and reduce stains. Additionally, bacterial colonization of ureteral stents occurs in 42% to 90% of cases, contributing to urinary tract infection (UTI), initial contamination during insertion, and prolongation of the procedure. Stents cause this problem. A study revealed that positive bacterial cultures from stent samples are a significant risk factor for urinary tract infection within 12 months after stent removal. Several strategies have been proposed to reduce bacterial accumulation, such as coated stents and, the application of drug solution technology. Especially for biodegradable coils [24].

2.2 Mechanism of Encrustation

The encrustation mechanism is intricate and multidimensional. Following stent implantation, a conditioning film composed of glycoproteins unique to the patient's tissue and urine composition is applied right away. [25] . The relationship between bacterial biofilm formation and encrustation is not well understood. Bacterial biofilms may facilitate encrustation and crystal precipitation. On the other side, encrustation may serve as a breeding ground for bacterial biofilms and germs, which may cause urosepsis in patients who already have stents placed. However, any material that covers a stent changes its inherent physical characteristics (such as a bacterial biofilm or protein conditioning layer), which might lead to the formation of crystals on the stent surface. Furthermore, the longer the stent has been in use, the more time it has for its surface characteristics to alter and solidify. [26]. Since biofilms can be made up of urease-producing bacteria (Proteus, Pseudomonas, Klebsiella, etc.) that can break urea into ammonium, increasing the pH of the urine and enabling the precipitation of struvite on the Double-J stent surface, biofilm

creation. [27]). But encrustations can also happen in sterile settings. Calcium oxalate was shown to be the most prevalent component on Double-J stents [28]. Urine parameters including pH, supersaturation of crystallizing chemicals, and lack of crystallizing inhibitors may thus be very important. [29]. Individualized preventative interventions that address the metabolic urine changes associated with ureteral stent encrustation may lessen associated consequences. Our goal was to ascertain how metabolic urine conditions relate to the development, degree, and make-up of encrustations on ureteral stents in individuals with stone formation [30].

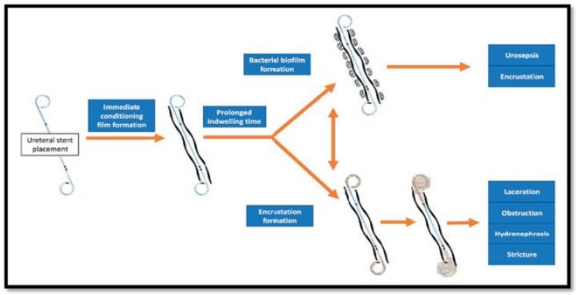

Figure 1 Mechanism of Encrustation Ureteral Stent

3.Recent Analytical Techniques for Encrustation in Ureteral Stents

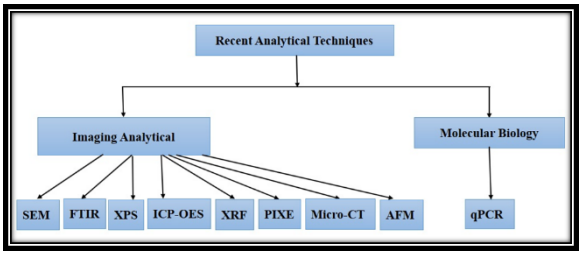

Diagram 1 Recent Analytical Techniques for Encrustation in Ureteral Stents

3.1 Imaging Analytical Techniques of Encrustations Ureteral Stent

3.1.1 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is a powerful imaging technique often used in engineering and medical research to examine the surface morphology and microstructure of materials. When applied to the analysis of ureteral stents, SEM provides high-resolution images that reveal fine details about the stent's surface, such as encrustation, corrosion, and wear. Ureteral stents, typically made of materials like silicone, polyurethane, or metallic alloys, are prone to encrustation when exposed to urine and its mineral content. This encrustation can lead to reduced stent functionality, increased risk of infection, and complications like blockage or damage to the ureter. SEM allows for the identification of various types of crystalline deposits, such as calcium phosphate, magnesium ammonium phosphate, or uric acid crystals, which contribute to encrustation. By analyzing the morphology of these deposits, SEM helps in understanding the underlying mechanisms of encrustation, which can inform the development of improved stent materials or coatings that resist biofilm formation and crystal deposition. Engineering solutions such as surface modification, anti-fouling coatings, or the use of advanced materials with better resistance to encrustation are being explored based on insights gained from SEM studies. For instance, coatings like hydrophilic or antibacterial layers are being designed to reduce the likelihood of encrustation and extend the operational life of stents [31] [32] These SEM analyses are crucial for optimizing stent design, improving patient outcomes, and enhancing the overall performance of medical devices in urology.

3.1.2 Fourier-transform infrared spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) is an essential analytical technique for studying encrustation on urethral stents, which are used to maintain urethral patency in patients with urinary obstructions. Encrustation refers to the accumulation of mineral deposits, such as calcium phosphate, calcium carbonate, and magnesium salts, which can form on the stent surface due to interactions with urine. This process can lead to stent blockage, irritation, or infection, significantly impairing its functionality. FTIR works by irradiating the stent's surface with infrared light, which excites the molecular bonds in the encrustation. The resulting absorption spectra provide detailed information about the chemical structure and functional groups present. Specific peaks in the FTIR spectrum, such as those around 1000–1100 cm^{-1} for phosphate compounds or 1400 cm^{-1} for carbonate deposits,

can be used to identify the types of minerals in the encrustation [33]. The technique is particularly valuable for non-destructive analysis, allowing researchers to study the chemical composition of encrustations without damaging the stent. Moreover, FTIR can be used to assess the effectiveness of surface modifications or coatings designed to prevent encrustation, providing insights into how different materials interact with urinary components [34] Overall, FTIR enhances the understanding of encrustation mechanisms and supports the development of more biocompatible, durable stent materials that are resistant to mineral buildup [35].

3.1.3 X-ray Photoelectron Spectroscopy

X-ray photoelectron spectroscopy (XPS) analysis is a surface-sensitive technique widely used in the engineering of medical devices, including ureteral stents, to investigate the chemical composition and elemental state of the materials used. XPS works by bombarding the sample surface with X-rays, causing the ejection of photoelectrons from atoms on the surface. By measuring the kinetic energy and intensity of these emitted electrons, XPS provides detailed information about the chemical bonding, oxidation states, and elemental distribution within the top few nanometers of the surface (typically 1–10 nm). In the context of ureteral stents, XPS is particularly valuable for assessing surface modifications such as coatings or bioactive layers that are engineered to enhance biocompatibility, prevent encrustation, or reduce the risk of infection. For instance, a study by Peppas et al. (2012) [36] demonstrated how XPS could be used to characterize surface functionalization on polymeric stents for improved drug delivery and adhesion. Similarly, XPS has been employed to analyze the titanium oxide layers on stents, revealing their corrosion resistance and biocompatibility [37]. Furthermore, XPS helps in understanding the interaction between the stent material and biological fluids, providing insights into the degradation processes or surface contamination over time. Overall, XPS serves as a crucial tool for optimizing the material properties of ureteral stents, contributing to safer and more effective designs.

3.1.4 **Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)**

Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) is a highly sensitive analytical technique commonly used for detecting and quantifying elements in various materials, including ureteral stents. From an engineering perspective, ICP-OES offers precision in identifying trace metal contaminants and understanding the elemental composition of stent materials, such as stainless steel, titanium, or nickel-based alloys. The technique works by introducing a sample into an argon plasma, which reaches temperatures of up to 10,000 K, causing the atoms in the sample to ionize and emit light at characteristic wavelengths. These wavelengths are then detected and quantified to provide information about the elements present in the material. For ureteral stents, ICP-OES can be critical in ensuring the stent's material composition meets biocompatibility and corrosion resistance standards, which are essential for long-term implantation and minimal adverse reactions. Furthermore, it can help engineers assess the quality control of the manufacturing process by detecting impurities or inconsistencies in material composition that could affect the stent's performance, durability, and safety. Studies have demonstrated ICP-OES's application in the analysis of biomaterials, where it has been used to measure elements such as calcium, phosphorus, and trace metals, which can influence the stent's functionality and the biological response of the body to the implant [38] [39] Thus, ICP-OES serves as an invaluable tool in the development, quality assurance, and regulatory compliance of ureteral stents.

3.1.5 X-ray fluorescence

X-ray fluorescence (XRF) analysis is a non-destructive technique used to determine the elemental composition of materials by measuring the fluorescent X-rays emitted from a sample when it is exposed to high-energy X-rays or gamma rays. In the context of ureteral stents, XRF can be employed to assess the material integrity and composition of the stents, particularly to detect encrustation or mineral deposits that may form on the stent surface over time. Encrustation is common in ureteral stents, where urinary salts, such as calcium phosphate and oxalate, precipitate and accumulate, leading to blockages, infections, or reduced stent functionality. From an engineering perspective, understanding the extent of encrustation is vital to improving stent design, as it influences the choice of materials, surface treatments, and coating technologies to reduce encrustation and enhance the stent's biocompatibility and longevity. XRF analysis offers advantages in this regard because it can rapidly identify and quantify elements like calcium, phosphorus, and magnesium that are typically involved in encrustation without requiring complex sample preparation or invasive testing. Previous studies have applied XRF to assess the formation of mineral deposits on stents and to investigate how surface modifications (e.g., coating with hydrophilic materials or biocompatible polymers) can minimize such encrustation [40] [41]. In this way, XRF serves as a valuable tool in advancing the development of more effective, durable ureteral stents in urological medicine.

3.1.6 Particle-Induced X-ray

Particle-induced X-ray Emission (PIXE) is a sophisticated analytical technique used to determine the elemental composition of materials by bombarding them with high-energy protons or other heavy ions. In the context of urethral stents, which are medical devices inserted into the urethra to prevent blockages or obstructions, PIXE can be employed to study their surface composition, corrosion behavior, and any encrustation or deposition of materials that might occur over time. Encrustation refers to the accumulation of minerals, such as calcium or magnesium salts, on the surface of the stent, which can lead to complications such as blockage or infection. From an engineering perspective, understanding the elemental build-up on urethral stents through PIXE allows for the optimization of material selection, surface treatments, and coatings to improve the biocompatibility and longevity of the stents. Research has shown that PIXE can accurately quantify the levels of different elements, helping to identify the specific encrustation materials and assess how different stent designs or coatings affect encrustation formation [42]. Moreover, PIXE provides a non-destructive method for evaluating stent materials and their interactions with bodily fluids, facilitating better engineering of stents more resistant to encrustation and other complications. References like Bucur et al. (2013) [43] and Soldo et al. (2019) [44] provide valuable insights into the application of PIXE for medical device analysis.

3.1.7 Micro-Computed Tomography

Micro-computed tomography (Micro-CT) analysis is a non-invasive imaging technique used to study the structure and performance of ureteral stents, particularly in the context of encrustation, a common complication. Ureteral stents are often used in medical treatments for obstructed urinary flow, and encrustation occurs when minerals, typically calcium salts, deposit on the stent's surface, leading to potential blockages, infections, and discomfort. From an engineering perspective, micro-CT allows for high-resolution, three-dimensional imaging of the stent, providing insights into the distribution, morphology, and extent of encrustation over time. Unlike traditional imaging methods like X-ray or ultrasound, Micro-CT can capture fine details of both the internal and external surfaces of the stent without the need for physical sectioning. This makes it an invaluable tool in evaluating the impact of stent material, surface coatings, and anti-encrustation treatments. Studies have used Micro-CT to quantify encrustation in a way that enables a better understanding of the stent's mechanical integrity and performance under prolonged use. The ability to visualize the changes in stent morphology as a result of encrustation also aids in the development of more effective materials and designs for minimizing these

Issues. Engineering advancements in micro-CT scanning have improved the resolution and computational analysis of these images, allowing for more precise evaluation and optimization of stent technologies [45] [46].

3.1.8 Atomic Force Microscopy

Atomic Force Microscopy (AFM) is a powerful imaging and analysis technique that can be used to study the surface properties of materials at the nanoscale. In the context of ureteral stents, AFM is valuable for examining the encrustation process, which refers to the deposition of mineral and proteinaceous material on the surface of the stent, typically calcium phosphate, oxalate, or uric acid. These encrustations are problematic as they can cause stent blockage, inflammation, and discomfort for patients. AFM analysis provides high-resolution topographical images, allowing for the examination of surface roughness, morphology, and the distribution of encrusting deposits. The ability to measure nanoscale changes in surface structure is crucial because surface roughness is known to influence the adhesion of encrusting materials. Additionally, AFM can be coupled with other techniques like force spectroscopy to assess the mechanical properties of the encrusted layer, including its stiffness and adhesion strength. Engineering approaches to understanding encrustation involve the design of stents with smoother surfaces or those modified with anti-encrustation coatings to minimize the deposition of minerals and proteins. Studies have shown that surface modifications, such as hydrophilic or hydrophobic treatments, can reduce encrustation rates by influencing the interaction between the stent surface and the urinary environment [47] [48]. AFM analysis plays a critical role in evaluating these surface modifications by providing detailed insights into how changes in surface topography and chemistry affect encrustation behaviors.

3.2 Molecular biology Analytical technique for Encrustations

- **Quantitative Polymerase Chain Reaction**

Quantitative Polymerase Chain Reaction (qPCR) analysis is a powerful molecular biology technique used to quantify specific DNA sequences, offering high sensitivity and precision in detecting microbial colonization on surfaces such as ureteral stents. Ureteral stents, commonly used in urological procedures, can be prone to biofilm formation, which significantly increases the risk of urinary tract infections (UTIs) and stent obstructions. From an engineering standpoint, qPCR provides a detailed,

quantitative assessment of bacterial load on the stent surface, offering insights into the microbial dynamics and aiding the development of stent materials that can mitigate these risks. For instance, various studies have applied qPCR to evaluate bacterial colonization on ureteral stents, highlighting the role of biofilm-forming bacteria such as *Escherichia coli* and *Proteus mirabilis*, which are commonly associated with stent-related infections [49] By analyzing the DNA extracted from stent surfaces, qPCR allows for the detection of low-level infections that may otherwise go unnoticed with traditional culturing methods. This ability to precisely quantify bacterial presence is essential for understanding the mechanisms of infection and developing antimicrobial coatings or materials to prevent biofilm formation. Moreover, the application of qPCR in this context enables engineers to optimize the design of ureteral stents, improving patient outcomes and minimizing complications such as encrustation and recurrent UTIs [50] [51]. These studies demonstrate the importance of qPCR not only as a diagnostic tool but also as a guide for designing more effective medical devices in the field of urology.

Table 1 Summary of the review of the latest scientific literature relevant to the thesis study.

No	Types of Technique	Advantages	Disadvantages
1	Imaging - SEM	• High-resolution imaging • Elemental analysis • Useful for observing biofilms	• Expensive and labor-intensive.
2	Imaging - FTIR	• Composition Identification • Fast • Sensitive	• Limited to Solids
3	Imaging - XPS	• Elemental & Chemical Information • Surface Sensitivity	• Limited Depth Penetration: Cannot probe deeper encrustation layers.
4	Imaging - ICP-OES	• Multi-element detection • High sensitivity	• Limited surface chemical information
5	Imaging - XRF	• Fast and Simple • Elemental Analysis	• Surface-only Focus: Primarily analyzes surface composition, not bulk encrustation.
6	Imaging - PIXE	• Multi-element Detection • Surface and Bulk Analysis: Can analyze surface and some deeper layers of encrustation.	• Quantification Challenges: Accurate quantification can be challenging due to matrix effects and the need for calibration.
7	Imaging - Micro-CT	• High Spatial Resolution • Internal and Surface Analysis	• Cost and Accessibility: Requires specialized equipment, which can be expensive and less accessible.
8	Imaging - AFM	• High Surface Resolution • Mechanical Property Measurement: This can measure surface stiffness and adhesion, which may be relevant for understanding encrustation properties.	• Slow Scanning: The process can be time-consuming, especially for large or complex samples
9	molecular biology - qPCR	• Sensitive Detection • Specificity: Can target specific genes or pathogens, helping to identify the microbial species contributing to encrustation. • Versatile: Useful for analyzing the biological aspect of encrustation, especially in infections or biofilm-related encrustation.	• Requires DNA Extraction: Involves extracting DNA from the stent, which can be challenging and may not represent the entire encrustation.

4.Results and Discussion

The results of the analytical techniques used to study encrustation in ureteral stents reveal a detailed picture of the composition, structure, and mechanisms behind the deposits. Scanning Electron Microscopy (SEM) provides high-resolution images of encrustation morphology, showing crystalline formations such as calcium oxalate, hydroxyapatite, and struvite, while Energy Dispersive X-ray Spectroscopy (EDX) confirms the elemental composition, highlighting the presence of calcium, phosphorus, and magnesium. X-ray Diffraction (XRD) identifies the crystalline phases of the encrustation, revealing the specific salts that form, while Fourier Transform Infrared Spectroscopy (FTIR) detects both inorganic and organic components, suggesting the involvement of proteins or glycosaminoglycans. X-ray Microtomography (Micro-CT) offers three-dimensional reconstructions of the encrustation, showing its impact on stent flow resistance, and Atomic Force Microscopy (AFM) characterizes surface roughness, which correlates with encrustation adherence. Finally, microbiological analysis uncovers bacterial involvement, particularly with urease-producing organisms in cases of struvite formation. Together, these techniques provide a comprehensive understanding of the factors contributing to encrustation, emphasizing the role of both chemical and biological processes in stent obstruction, and highlighting the need for innovative materials and coatings to reduce encrustation and improve stent performance.

5. Conclusion

The pursuit of high-quality research articles to explore the precise mechanisms of ureteral stent encrustation is crucial for developing effective prevention and treatment strategies and designing better anti-encrustation stents. It's essential to acknowledge the complexity of urine composition, as metabolic conditions significantly influence the formation, composition, and severity of encrustation, along with the interactions between ureteral stents and various organic substances in the body. In summary, this study facilitates a range of analyses—including quantitative microbiological, biochemical, and molecular investigations of biofilms from ureteral stents—which may shed light on the relationship between patient morbidity and stent biofilm formation. Such advancements will equip physicians, clinicians, researchers, and medical device manufacturers to tackle encrustation effectively, turning it into a challenge of the past.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Halah Hadi Salih: Conceptualization, Investigation, Data collection, Writing – review and editing. Nabeel Kadim Abid AL Sahib: Examine and correct the manuscript, supervision, Writing – review and editing. Hayder Ismael Jawad: Supervision, Writing – review and editing.

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