

Review

Natural Organic Matter Character in Drinking Water Distribution Systems: A Review of Impacts on Water Quality and Characterization Techniques

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Abstract: Natural Organic Matter (NOM) in water arises from decomposed plant and animal matter and is ubiquitous in drinking water sources. The variation in NOM concentrations and characteristics, influenced by events like floods and droughts, plays a crucial role in water treatment efficiency and water quality received by the public. For example, increased NOM concentrations necessitate higher levels of coagulants and disinfectants, leads to the formation of disinfection by-products (DBPs), and plays a key role in biofilm development. When considering impacts of NOM, it is not only the presence or concentration but the makeup or proportion of varying sub-groups which can impact water quality. Formation of DBPs, corrosion and scaling, pollutant transport, aesthetic deterioration, and biofilm growth are dependent on the relative composition of NOM within the distribution system. Although the role of NOM concentration and characteristics is well studied during treatment, the impacts of residual NOM in water distribution systems have received less attention. In particular, it is clear, due to the varying roles of NOM sub-groups, that greater consideration of NOM characteristics in distribution systems is needed. This paper reviews the broad implications of NOM characteristics for water distribution systems and explores challenges and opportunities in NOM characterization within distribution systems. Furthermore, the influence of NOM characteristics in premise plumbing is examined. The review highlights the necessity for precise NOM characterization and real-time monitoring, aiming to strengthen water distribution system resilience.

Keywords: natural organic matter character; water treatment; distribution systems; water quality monitoring



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1. Introduction

Natural Organic Matter (NOM) in water is a complex grouping of compounds resulting from biological and physicochemical processes associated with the decomposition and metabolism of plants and animals [1]. With its varied chemical compositions, ranging from simple aliphatic structures to more complex coloured aromatics, NOM stands as a diverse array of organic compounds [2]. The diversity of compounds results from a range of transformational processes acting on organic matter in the environment [3]. The diversity results in broad ranges of surface charges, molecular size and weight, structures, and functional groups [4]. Due to the complexity of NOM as a heterogeneous mixture, the specific chemical makeup of NOM is challenging to define precisely. Sub-groups of NOM are often operationally or functionally defined to identify groups of chemicals with similar properties [5]. A typical high-level separation of NOM is into hydrophobic and hydrophilic fractions [6]. Hydrophobic acids, predominantly termed humic compounds, constitute the major segment of the dissolved organic carbon (DOC) in water, while the hydrophilic fraction is typically at a lower relative concentration and consists of molecular groups like carbohydrates and proteins [6,7].

Water treatment plants strive to minimize the levels of NOM, since residual organic matter post-treatment can be of significant concern within distribution systems. While most NOM compounds are not directly concerning and are non-toxic, the persistence of NOM during distribution can lead to deterioration of water quality. For example, the presence of NOM results in loss of disinfectant residuals, critical for preventing microbial contamination [8–10]. Consequently, this can foster the growth of biofilms that can degrade the infrastructure of the water distribution system along with water quality [11–13]. Furthermore, the interaction of NOM with infrastructure materials can influence the leaching of potentially hazardous substances such as lead and copper, and increase concentrations of complexed heavy metals and organic pollutants [2,14,15]. In addition, the presence of NOM in distribution systems can complicate the management of disinfection by-products (DBPs), as it serves as a precursor for their formation [2,16]. Aside from health considerations, NOM also contributes to aesthetic issues such as water discolouration and undesirable taste and odour, which can undermine public trust in the water supply [17].

Sub-groups of NOM compounds have varying roles in affecting water quality and reactions in the distribution system. For example, distinct sub-groups of NOM can preferentially react to form different DBP species, making it challenging to anticipate and mitigate the formation of DBPs without information on NOM characteristics [18]. Hydrophilic and low molecular weight NOM has been observed to react preferentially with bromine and iodine, although hydrophobic and high molecular weight NOM generally results in greater production of halogenated chlorination by-products [19]. Metals of concern in plumbing, such as lead, form complexes with some NOM sub-groups which may affect their transport, bioavailability, and ultimately public exposure [20]. Bioavailability and the generation of biofilm in distribution systems has also been found to be dependent on the relative make-up of NOM [21,22].

While previous research paints a clear picture that the composition of NOM during treatment and in the distribution system influences changes to water quality and overall potential health risk, there are limited methods to measure and track distinct NOM sub-groups in distribution systems. The majority of NOM characterization methods require grab sampling and complex lab analysis [4]. Furthermore, the nature of distribution systems dictates a need to monitor a spatially diverse network, which further limits the applicability of grab sampling or complex analyses to carry out NOM characterization. Seasonal and climatic events like floods and droughts can inadvertently lead to variations in NOM concentrations in water bodies, exacerbating management challenges [2,23]. The variability of NOM character and concentration in the source results in corresponding NOM dynamics during treatment and in the distribution system. The cumulative impact of NOM and inherent difficulties in monitoring water quality in distribution systems underscores the importance of addressing its variability to ensure the safety, aesthetics, and overall integrity of the water supply.

The dynamics and impacts of NOM characteristics in source waters and during treatment has been well-documented and extensively studied, with a substantial body of literature dedicated to understanding its treatment and removal methods [17,24–26]. Since NOM characteristics are dependent on the biological and physiochemical processes occurring the watershed, seasonal changes in NOM character are pronounced and can result in varying treatment efficacy throughout the year [27]. As examples, previous work has highlighted changes in biological filtration performance [27] and coagulation performance [28] due to natural changes in the properties of NOM over seasons. Several reviews have covered the role of distinct NOM sub-groups in the performance of various treatment processes, including, but not limited to, coagulation [29], membrane filtration [30], and adsorption [24], as well as methods to characterize NOM [2]. However, to our knowledge, the dynamics of residual or leftover NOM character within water distribution systems have not been comprehensively reviewed. There is a need for focused consideration of NOM characteristics on the behaviour and impact of NOM after conventional treatment processes and as it moves through distribution networks. This review aims to address this gap by

exploring the role of NOM within water distribution systems, particularly emphasizing the challenges posed by residual NOM. Furthermore, this review aims to synthesize recent advancements in the analysis and quantification of NOM in the context and limitations imposed by distribution systems.

2. Impacts of NOM and NOM Characteristics on Distribution Water Quality

2.1. Chlorine Interactions and DBP Formation in Water Distribution Systems

Chlorine-based reagents such as chlorine, chlorine dioxide, or chloramines are heavily used for drinking water disinfection due to their efficiency, low cost, and effectiveness in the inactivation of a wide range of pathogens. However, chlorine-based reagents react with NOM and/or other halogens such as bromine or iodine in water to produce DBPs [31]. Over the past years, several DBPs have been identified, with varying degrees of correlation, and possible risk to human health [32]. As such, drinking water standards have aimed at limiting DBP exposure by regulating two commonly occurring groups, including trihalomethanes (THMs) and haloacetic acids (HAAs). By mass, THMs and HAAs are the predominant sub-groups of all halogenated by-products produced from the use of chlorine [33]. Although THMs and HAAs are characterized as low-toxicity by-products, they are utilized as surrogates for other toxic byproduct formations in the water. The US Environmental Protection Agency has set maximum contaminant levels of 80 µg/L and 60 µg/L for THMs and HAAs, respectively [34]. As a result of targets set for THMs and HAAs, water treatment plants have modified, changed, or optimized treatment to reduce the potential formation of DBPs. Such means include optimizing treatment processes for NOM removal or advocating for different forms of disinfection.

DBP formation persists beyond initial water treatment, continuing within the distribution system as the interaction between residual disinfectants and organic precursors is influenced by varying water conditions [35]. Despite pretreatment effectively reducing NOM and initial DBP formation, the residual chlorine in the water distribution system can react with remaining organic matter, leading to further DBP production [31]. This ongoing process is exacerbated in systems with extended residence times, allowing for more extensive reaction opportunities between disinfectants and organic precursors [36]. The presence of NOM, even in reduced quantities post-treatment, in conjunction with residual chlorine, causes DBP formation and is a continuous concern within water distribution systems [36]. Maintaining a chlorine residual is not merely a consequence but an intentional strategy for safeguarding public health. This approach effectively prevents microbial regrowth in water distribution systems. However, while crucial for health, this deliberate use of chlorine also contributes to the continuous formation of DBPs, presenting a critical balance between health safety and managing disinfection by-products. The variables that influence the formation and levels of DBPs include the properties of NOM, the choice of disinfectant, as well as environmental and operational factors such as temperature, pH, and the time water spends in the system (hydraulic residence time) [37]. These factors together create a dynamic environment where DBPs can form and accumulate, underscoring the need for thorough investigation and management strategies.

Hydraulic residence time has a strong positive correlation with increased THM formation [38]. Kinetic studies have identified that, depending on chemical composition, there are NOM groups that react quickly to form THMs, with other compounds contributing to slow kinetics [39]. As such, it can be expected that a significant portion of DBPs will form within hours, with continuing but different reaction kinetics over longer periods. DBP concentrations have been shown to continuously increase even for extreme residence times of >10 days [36]. As water remains stagnant in a system or reservoir, the water quality deteriorates over time, resulting in reduced levels of disinfectant and greater concentration of DBPs [38]. However, managing residence times is complex, due to the inconsistency of water demand patterns of consumers, WDS size, and uncertainties in hydraulic modeling [40].

The diverse properties and composition of NOM in varying source waters and as a result of treatment applied impact the type, quantity, and toxicity of DBPs formed.

Many studies have observed high degrees of variability in DBP formation potentials between water sources and over seasons [19,35,41], even when total organic concentrations (i.e., DOC) were constant [36]. For THMs and HAAs, several studies have observed preferential formation from high molecular weight and hydrophobic NOM [19,42,43]. Other NOM fractions have been identified to preferentially form specific chlorination DBPs. Chlorination can promote reactions with other halogens (bromide and iodide). Preferential reactions of hydrophilic NOM with bromide and iodide have been reported [19,44]. Organic matter from cyanobacterial blooms, rich in nitrogen, has been identified as precursors for nitrogenous DBPs [45]. The molecular weight of the NOM has also appeared to be a strong influencing factor on the DBPs produced. While high molecular weight NOM promotes chloroform formation, decreasing molecular weight is associated with increased brominated DBP formation [42].

Since NOM characteristics influence the DBPs produced, it is of interest to utilize analytical techniques that can specifically identify and quantify the sub-set of precursor material. SUVA, or Specific Ultraviolet Absorbance, is calculated by dividing the UV absorbance at 254 nm (m^{-1}) by the DOC concentration (mg L^{-1}). This calculation provides an index of the aromatic content in the organic matter [46]. It has been suggested that NOM with high SUVA values, indicative of carbon-rich substances, are significant precursors for carbonaceous DBPs such as THMs and HAAs [42]. These high-SUVA NOMs, which make up a substantial portion of the total organic mass and exhibit high carbon-to-nitrogen (C/N) and carbon-to-oxygen (C/O) ratios, are closely associated with the formation of these DBPs [18]. High-SUVA NOMs, characterized by their aromatic nature and long-wavelength humic-like fluorescence signals, predominantly exist in high molecular weight fractions. Conversely, NOM with low SUVA values, which can be either nitrogen-rich or oxygen-rich, exhibits varied DBP formation behaviours. Nitrogen-rich NOM, for example, yields both carbonaceous and nitrogenous DBPs, while extremely low-SUVA oxygen-rich NOM produces significantly lower levels of both types of DBPs [18]. Ultimately, a comprehensive grasp of NOM's properties, ranging from its molecular weight to its chemical composition and optical traits, is crucial for anticipating and reducing DBP formation.

There is variation in pipe materials used to construct distribution systems, based on supply, regulations, and cost. Pipe materials used will affect the formation of DBPs and the decay of disinfection residuals [47,48]. Due to its compressive strength to resist pressure from the earth, cast iron is the most commonly used pipe material for WDS worldwide [49]. Despite these advantages, it is easily corroded and is a source of iron ions that can further facilitate chlorine decay; this is exacerbated by the mass-transfer enhanced wall demand in aged ductile iron pipes, which leads to rapid chlorine decay and lower rates of DBP formation [50]. While PVC systems are more effective at maintaining a residual chlorine level, they present a challenge in controlling DBP formation. This is likely due to the fact that PVC pipe wall has minimal chlorine demand, allowing more chlorine to remain in the water to react with organic matter to form DBPs [51]. Previous work has reported that the use of PVC vs. ductile iron can result in a 36% increase in THM formation and a 60% decrease in residual chlorine decay over time [52]. Moreover, the speciation and DBP type produced in WDS can also be influenced by pipe wall material. The specific properties of steel, which may include the presence of other metals in steel alloys such as nickel or chromium, could also influence the types and quantities of DBPs formed. The electrochemical properties of steel in contact with water and disinfectants might lead to different corrosion mechanisms compared to cast iron, potentially influencing the types of DBPs produced. The corrosion of iron pipes in drinking water distribution systems facilitates the formation of nitrogenous disinfection by-products (N-DBPs) by releasing iron particles that shield microbial communities, promoting biofilm growth and the production of organic nitrogen-rich extracellular polymeric substances, which then react with chlorine disinfectants to form N-DBPs [48]. Generally, biofilms and microbial activity influencing chlorine decay adhere preferentially on metal pipes such as ductile iron and steel rather than plastic pipes [53].

In water distribution systems, microorganisms tend to grow on pipe walls by feeding on pipe wall deposits, NOM, and biodegradable organic compounds as a nutrient source, which over time encourages the formation and sustenance of biofilms [54]. Biofilms are more abundant in low-velocity sectors within a WDS, where high-pressure conditions are not maintained and hydraulic residence time of water is often long [55]. Biofilms continue to feed on dissolved organic matter and excrete extracellular polymeric substances (EPS), influencing chlorine decay and DBP formation [31]. EPS are complex organic matrices within biofilms composed of biopolymers and other organic matter fractions that act as precursors to DBP formation [48]. Consequently, the contribution from bacteria-derived precursors such as EPS has been demonstrated to increase total formed THMs by as much as 12% [56]. Since NOM and nutrients in the WDS promote microbial activity and biofilm formation [56], NOM can contribute to DBP precursors both directly as well as through the promotion of EPS.

Water treatment plants have predominantly focused on the control and monitoring of regulated DBPs (R-DBPs), including THMs and HAAs. However, there is a growing concern for unregulated DBPs (UR-DBPs) due to their greater potential toxicity. Studies of relative toxicity indicate that regulated DBP groups exhibit limited cytotoxicity, while unregulated DBP groups (UR-DBPs) demonstrate greater toxic effects, suggesting the need for a more comprehensive analysis of DBP-mediated risks in water distribution systems [16,57]. A review article by Mian et al. [58] listed the most commonly identified UR-DBPs in WDS, including halonitromethanes (HNMs), halo ketones (HKs), and haloacetamides (HAMs), among others, to result in potentially elevated risk. Research has identified that specific sub-groups of NOM have greater association with the formation of specific UR-DBPs. Fang et al. [43] identified that hydrophilic microbially derived protein-like biopolymers are predominant precursors for haloacetaldehydes and haloacetonitriles. Tryptophan- or protein-like signals have also been observed to correlate strongly with haloacetonitrile formation [45].

2.2. Corrosion and Scaling

Corrosion in WDS raises a significant concern for water utilities and end users that rely on safe water quality. Elevated levels of corrosion can result in a number of problems, such as deteriorating water quality, pipe structural damage, rising maintenance costs, and potential health risks for customers. Corrosion in pipes occurs from complex processes that release metal ions that will eventually accumulate and gradually scale [59]. This process is impacted by the presence and character of NOM, along with many other environmental conditions, with both protective and accelerating effects possible.

Iron is the most used pipe material in WDS globally, and has been used throughout centuries of water transport [60]. The interplay between water velocity, NOM composition, and iron pipe corrosion is a complex one, with various studies contributing insights into this phenomenon. Previous results suggest a diverse range of effects of NOM composition on corrosion rates. Gruškeviča et al. [61] highlighted the differential impacts of very hydrophobic acids (VHA), mostly composed of humic substances, and charged hydrophilic acids (CHA), predominantly non-humic substances. While VHA presence is not significantly associated with changes in corrosion rates, an increase in CHA concentration is linked to higher rates of corrosion. Moreover, NOM's interaction with free iron to form complexes can reduce corrosion rates under specific pH conditions [62].

Corrosion of copper pipes is also influenced by NOM. Within a concentration range of 0 to 1.0 mg/L DOC, the effects of NOM on corrosion are influenced by both its concentration and hydrophobicity [63]. However, for DOC concentrations exceeding 1.0 mg/L, the impact of NOM becomes largely independent of dosage and hydrophobicity. Notably, NOM not only alters the surface morphology and corrosion rate but also significantly affects metal leaching, with a pronounced increase in metal concentration when DOC is raised from 0 to 0.1 or 0.2 mg/L. The mechanism behind NOM-promoted copper leaching involves complexation and colloidal mobilization/dispersion. NOM can also alter the copper

corrosion process by interfering with the natural aging of pipe scales, which maintains higher free copper concentrations in water [64]. The presence of NOM on pipe scales can lead to increased copper release during water stagnation, due to its influence on copper complexation capacity. The role of NOM in mitigating pitting attacks on copper suggests that its presence can be both protective and corrosive under different conditions. The interaction of NOM with biofilms, which contain high concentrations of extracellular polymeric substances, adds another layer of complexity, affecting redox conditions and the biochemical activity within the pipes [65]. While the hydrophilicity of NOM has a minimal direct impact on corrosion, other attributes, such as its surface activity, play a more dominant role. The type of NOM also has distinct implications; for instance, copper release is more affected by the presence of the highly hydrophobic than by less hydrophobic variants [63]. In essence, the presence and type of NOM can profoundly influence the corrosion dynamics of copper, emphasizing the need for a deeper understanding of these interactions in real-world settings.

Additionally, the interplay between NOM and calcium-carbonate equilibrium presents another dimension to scaling in WDS. Calcium ions can precipitate with complex organic anions from NOM that lack a well-defined crystal structure, forming gel or colloidal materials, which may then incorporate into more crystalline forms. This co-precipitation process, combined with other physio-chemical and biological processes, contributes to the formation of calcium carbonate deposits, affecting the scaling dynamics in WDS [66]. Furthermore, the Calcite Surface Complexation Reaction Model reveals how organic ligands in NOM, interacting with calcite surfaces, can influence calcite growth rates. For example, certain DOM complexation reactions can form surface complexes, such as CaHPO_4 , which inhibit calcite growth, thereby impacting the formation and dynamics of calcium carbonate deposits in water systems [67]. Understanding these interactions is crucial for effectively managing scaling and maintaining the integrity of water distribution infrastructures.

While the corrosion mechanism can be both electrochemical and microbial, NOM stands out as a pivotal factor. A significant observation is the strong adsorption of NOM onto corrosion scales, facilitated by interactions between its acidic functional groups and the hydroxylated oxide surface sites of the corroded material [68]. This interaction not only modifies the structure of NOM but also creates an environment conducive to bacterial proliferation. Waters rich in NOM are particularly prone to supporting such growth, which may subsequently enhance biologically mediated corrosion, as evidenced by the presence of sulfides in these waters and the resulting corrosion products [69]. Biofilm is composed of several bacteria species that accelerate metal corrosion in steel and iron pipes [70]. These species can promote corrosion via synergistic interactions of abiotic corrosion, metal surfaces, metabolites, and bacterial cells [70]. On the other hand, some findings showed that biofilm can protect metal from corrosion [71]. Concurrently, the interaction of NOM with reducing bacteria, including iron-reducing bacteria (IRB) and nitrate-reducing bacteria (NRB), plays a pivotal role in corrosion dynamics within WDS. Specifically, IRB, under the influence of NOM, can mitigate the corrosive actions of iron-oxidizing counterparts, while NRB, influenced by NOM, can alter the redox state of iron, further complicating the corrosion process [72]. Teng et al. [73] investigated the role of biofilm on its ability to influence corrosion and found that the presence of biofilm could expedite corrosion in the initial stages but can inhibit corrosion after 7 days. Corrosion promotion at the initial stages was influenced by iron bacteria that would respire iron ions. The corrosion inhibition was linked with iron-reducing bacteria that reduce Fe^{3+} to Fe^{2+} . Corrosion mechanisms are altered by the continuous change of biofilm microbial diversity in a distribution system [73]. This bacterial activity, intertwined with the corrosion process, can induce marked changes in water parameters, highlighting the cyclical and symbiotic relationship between water quality, NOM, and corrosion [69]. Although NOM concentrations have proven to influence corrosion rates and scaling, other factors such as temperature, pH, alkalinity, biofilm, infrastructure age, and hydraulic properties of water all affect corrosion in distribution systems and should further be examined by water utilities to develop remediation against

corrosion. These findings resonate with the wider literature that emphasizes the need for a nuanced understanding of NOM's role in corrosion processes, suggesting that the protective mechanisms of water systems are influenced by a complex array of factors beyond the mere presence of organic matter.

2.3. Pollutant Transport

It has been established that NOM has a high adsorptive affinity for many pollutants such as metals, radionuclides, pathogens, and emerging contaminants (e.g., microplastics and nanoplastics), which can facilitate their transport [74]. This is particularly significant in light of recent findings that aging infrastructure, specifically pipes made from materials such as PVC and PTFE, can leach microplastics into the water. These microplastics, once in the water system, are then susceptible to interaction with NOM [75]. Upon interacting with NOM, microplastics (MPs) and nanoplastics (NPs) develop an eco-corona (EC) or transform into biogenic aggregates. This association changes the physicochemical attributes of the plastics, affecting their transport, deposition, and interactions within distribution systems, and ultimately their environmental persistence. Various NOM types, from allochthonous sources such as humic and fulvic acids to autochthonous ones like extracellular polymeric substances, can associate with these plastics, thereby altering their dynamics [76]. Additionally, the presence of NOM can adjust the adsorption abilities of MPs and NPs, which might result in the entrapment and conveyance of other pollutants within the distribution network.

Metals can complex with NOM, which results in increased metal solubility. Therefore, the characteristics of NOM and its concentration plays a pivotal role in metal transport through distribution systems [74]. Complexation between NOM and metals can either be through the metal binding to an ionized site or displacing a proton [7]. Different metal ions with distinct affinities for various size fractions of NOM within distribution systems reinforce the understanding that these metals are seldom found as isolated, free hydrated ions; instead, they are often complexed with NOM. This complexation significantly influences the bioavailability and transport behaviour of metal ions like Fe and Al, which exhibit strong bonds with NOM, thereby enhancing their stability and transport within the system [20]. Conversely, metals like Zn and Pb form weaker complexes with NOM, which may affect their interaction with the infrastructure and their bioavailability [20]. As such, both NOM and metal ion characteristics can subsequently affect the degree and strength of complexation through the distribution system, with potential implications for public health due to variations in metal bioavailability [7]. This understanding is critical for water treatment and distribution management, as the characteristics of NOM and its complexation with metals like Fe and Al may necessitate adjustments in treatment processes to mitigate adverse effects. For instance, if NOM stabilizes Fe and Al in solution, preventing their precipitation, this could lead to higher levels of these metals at consumer taps, potentially affecting water quality and health outcomes. Similarly, the weak binding of Zn and Pb with NOM could result in these metals being more mobile and bioavailable, which is also a concern for consumer safety.

Corrosion sediments in water distribution systems refer to the particulate by-products that result from the corrosion of the system's pipes and infrastructure. These sediments can be composed of various materials, including rust (primarily iron oxides) from the corrosion of iron and steel pipes, precipitates from the interaction of water with pipe material such as copper or lead, and other mineral deposits that form as a result of chemical reactions within the pipes [77]. Studies have shown that fulvic acid is a common NOM component that adsorbs to corrosion sediments. The adsorption of fulvic acid onto corrosion sediments was found to depend on time, with almost 70% of fulvic acid removed during the initial stages of contact. This indicates that fulvic acid mainly accumulates on corrosion sediments through physical-chemical interaction [68]. Moreover, organic compounds adsorbed onto corrosion products serve as a source of highly bioavailable carbon. The process of adsorbing humic and fulvic acids onto iron oxide surfaces creates contact points between oxygen-abundant

functional groups and iron oxide surface sites, resulting in an expanded and exposed molecule that is susceptible to microbial attacks [68]. Previous work has identified that NOM adsorption capability to iron pipe corrosion scales is a function of pH [78]. As the pH fluctuates, the surface properties and reactivity of these iron oxides undergo changes which impact interactions with NOM. In addition, varying NOM sub-groups have preferential adsorption behaviour, where higher molecular weight fractions were observed to have a stronger affinity towards these surfaces, especially in more acidic environments. Not only does pH affect the surface properties of the iron oxides, but it also plays a vital role in the fate and transport of pollutants within the distribution system. As pollutants interact with the DOM-coated iron oxides, their mobility, reactivity, and potential health risks can be significantly altered [78].

2.4. Microbial Dynamics

The main priority for drinking water distribution is to deliver microbiologically safe and aesthetically acceptable water to customers. As such, a concern for treatment plants is the potential for microbial regrowth in the system that causes public health risks and taste and odour issues. Organic matter characteristics plays a significant role in shaping the microbial regrowth potential within drinking water distribution systems. Not all forms of organic matter present in these systems are equally accessible to the microorganisms, leading to the development of specialized measures to quantify the fraction that is biodegradable or assimilable by the resident microbial population. Within WDS, key indicators such as Assimilable Organic Carbon (AOC), Biodegradable Dissolved Organic Carbon (BDOC), and Total Organic Carbon (TOC) are employed to evaluate organic matter that influences microbial behaviour. TOC, in particular, serves as a broad marker for NOM, and is crucial for monitoring and controlling bacterial proliferation and microbial activity [79,80]. Elevated TOC suggests a high potential for microbial regrowth, and as such a focus on TOC reduction has been demonstrated to be a potent method for controlling bacterial activity. For instance, reducing TOC levels can potentially have a more substantial impact on suppressing bacterial proliferation than maintaining a chlorine residual [81]. However, TOC as a broad measure has limitations in accurately predicting the biodegradable fraction of NOM that directly contributes to microbial growth. For example, TOC in non-ozonated water comprises about 20% BDOC and 3% AOC, suggesting a significant portion of NOM might not directly contribute to microbial regrowth. For ozonated waters, the proportions of TOC as BDOC or AOC were found to be significantly higher, which implies that ozonation increases the biodegradable fraction [22]. These insights emphasize the importance of characterizing NOM, particularly its biodegradable fraction, to better understand and manage the microbial dynamics within distribution systems.

AOC's significance in water distribution systems stems from its ability to promote microbial growth, particularly in situations where residual chlorine levels are low. It is the portion of TOC that bacteria can easily assimilate and convert into cellular biomass [82]. In reclaimed water distribution systems with significant levels of AOC, microbial regrowth becomes particularly pronounced when the total and free residual chlorine levels drop below 0.36 and 0.09 mg/L, respectively [83]. Regrowth can result in violations of total coliform rules and introduce pathogens like *Mycobacterium avium* and *Legionella* spp. [84]. Previous studies have identified direct correlations between elevated AOC levels and increased coliform counts. Specifically, water systems with AOC concentrations exceeding 100 mg/L registered an 82% surge in coliform-positive samples, with coliform levels being 19 times higher than in systems where AOC levels were below 99 mg/L [85]. The dynamics between these TOC fractions and microbial activity in distribution systems can manifest in multifaceted challenges, ranging from the onset of opportunistic pathogens to aesthetic degradation and even biofouling [83]. Moreover, a study by Sambo et al. [21] at a South African treatment plant categorized NOM into hydrophilic, transphilic, and hydrophobic fractions, noting that the first two are particularly biodegradable and thus conducive to bacterial proliferation. The hydrophilic fraction, abundant in glucose and amino acids, was

found to be most supportive of bacterial growth. Such insights underscore the necessity for targeted NOM characterization and removal strategies to maintain water biostability.

2.5. Water Aesthetics

The aesthetics of water can be significantly altered due to the presence of NOM as it travels through distribution systems and premise plumbing. For example, humic and fulvic acids, which range from black to yellow in hue, are the primary contributors to the water colour [17]. A decrease in aesthetic quality in distribution systems can also be due to biological activity. Certain bacteria such as *Actinomyces* and cyanobacteria like *Microcystis* utilize organic matter and produce metabolites such as geosmin and 2-methylisoborneol that cause taste and odour problems in distribution system reservoirs. Additionally, sulphate-reducing bacteria produce hydrogen sulphide, which can result in taste and odour problems. Bacteria like *Pseudomonas* generate ‘swampy’ odours due to organic sulphides, and ferrobacteria also influence taste and odours [86,87].

Some DBPs, particularly chlorinated phenolic compounds, can induce aesthetic concerns, notably influencing the water’s taste and odour. For instance, compounds such as 2,4,6-trichlorophenol, with low odour thresholds, can contribute to chlorinous or medicinal odours in chlorinated waters [86]. When NOM with a high nitrogen content reacts with disinfectants like chlorine or chloramines, it can produce various odorous compounds. Specifically, under certain conditions, nitrogen-rich NOM can lead to the formation of odorous aldehydes, N-chloraldehydes, or nitriles. Amino acids, which are nitrogen-containing compounds, have been identified as the primary precursors causing odour in water [17]. These amino acids can be released into the water, either through the lysis (breakdown) of bacterial or algal cells or when proteins undergo oxidation [88]. Among the compounds formed, nitriles are particularly noteworthy. They have high odour threshold levels, meaning they need to be present in relatively large amounts to be detected by smell, and are such are not typically implicated in taste and odour events. However, when nitriles are produced, they can persist in water distribution systems for extended periods, sometimes even for more than 500 h (approximately 21 days) at 15 °C. Concentrations of such compounds may increase in the distribution system as a result of the release of amino acids or peptides from biofilm [89].

3. Premise Plumbing

Premise plumbing, which refers to the complex network of pipes, fixtures, and devices within buildings that distribute water after it enters from the main municipal line, is a critical determinant of the final drinking water quality for consumers. Conditions in premise plumbing systems differ markedly from those in the distribution system, due to smaller pipe diameters, varied pipe materials, more frequent changes in flow and pressure, and longer water stagnation times. These unique conditions can deteriorate water quality and provide a breeding ground for opportunistic pathogens [90]. Material selection in premise plumbing can influence the microbial community, potentially impacting water quality and the risk of corrosion. For example, the types of pipe materials used in these systems, such as copper and lead, can affect the propensity for microbial growth and the release of metals, leading to distinct challenges compared to materials like iron used in distribution systems [91].

3.1. Corrosion Dynamics and Contaminant Behavior

Despite the critical role of premise plumbing in delivering safe drinking water to consumers, there are knowledge gaps concerning the specific impacts of NOM within this environment. Quantifying and characterizing NOM in premise plumbing is not just an extension of what is known from distribution systems. Understanding the behaviour and effects of NOM in premise plumbing can provide insights into water quality changes at the point of use, inform treatment strategies, and guide the development of best practices for maintaining water quality within buildings and homes. NOM has been recognized as a

critical factor in influencing lead (Pb^{2+}) release dynamics, particularly in the context of galvanic corrosion. Arnold [92] observed that various plumbing materials exhibited increased lead release in the presence of NOM, necessitating higher doses of orthophosphate for effective corrosion control, especially in high-NOM waters. Further studies demonstrated a significant rise in dissolved lead concentrations—an average increase of $2320 \mu\text{g/L}$ —when NOM was introduced at a concentration of 7 mg C/L [93]. This marked increase in lead release is attributed to NOM's ability to complex with lead, thereby mobilizing dissolved lead and affecting the dispersion of lead-rich colloids. Moreover, the specific role of humic substances, a component of NOM, in influencing lead solubility was identified. The removal of humic acids from water resulted in a reduction in plumbosolvency, underscoring their role in complexing metals and maintaining them in solution [94].

NOM has also been found to influence the catalysis of copper corrosion products and n-nitrosodimethylamine (NDMA) formation [95]. NOM has an inhibitory effect on copper's catalytic activity in NDMA formation. This inhibition is intricately linked to two primary mechanisms: the swift consumption of chloramines by NOM, and the competitive complexation between NOM and copper, which subsequently lessens the formation of NDMA–copper complexes. The binding affinity of NOM with Cu(II) is influenced by multiple factors, including the types of functional groups present in NOM, pH, copper concentration, and the presence of other ions like Ca^{2+} and Mg^{2+} [95]. This affinity has significant implications, as observed in other studies, which have demonstrated that increased concentrations of Cu(II) can catalyze the formation of DBPs during the chlorination of humic substances. Higher levels of Cu(II) increase total organic halogen (TOX) and THM formation potential, with HAAs also rising, although to a lesser extent. These effects are exacerbated at high pH levels and in the presence of bromide ions, which lead to the production of brominated DBPs [96]. Future research must further delve into the effects of pipe materials on the genesis of disinfection by-products. The impact of lead ions leaching from piping on the acceleration or increase in DBP formation in premise plumbing is an under-explored area [97].

The finding from Peng et al. [15] that NOM can significantly reduce the retention of certain metals on corrosion scales is directly relevant to the issue of metal leaching in premise plumbing pipes. In premise plumbing systems, which often feature diverse pipe materials, including lead and copper, NOM can alter the interactions between these metals and the pipe surface, potentially increasing their mobility and leaching into drinking water. When NOM interacts with metals such as copper and lead, it can form complexes that hinder their adsorption onto iron corrosion scales [15]. This phenomenon is particularly crucial in premise plumbing due to the frequent episodes of stagnation and varied flow rates, which can result in higher exposure times between the water, NOM, and pipe materials. This increased contact time may enhance the formation of metal-NOM complexes, thereby elevating the risk of metal leaching.

3.2. Chloramines and Nitrification

Chloramines have emerged as a preferred secondary disinfectant in water distribution systems, primarily due to reduced THM and HAA formation and longer persistence than free chlorine [98]. This increased stability and its effectiveness in reducing heterotrophic plate counts have contributed to its widespread adoption. Additionally, chloramines demonstrate a lower reactivity with iron corrosion products on pipe surfaces, enhancing their capability to control biofilm bacteria, which is particularly beneficial in premise plumbing systems [99]. Nitrification is a pivotal process in premise plumbing that can significantly influence the stability of chloramines. This process is initiated by free ammonia, which can originate from chloramine decay, overdosing of ammonia during chloramine formation, or naturally occurring ammonia in groundwater. Nitrification involves the microbial conversion of ammonia to nitrite and subsequently to nitrate, facilitated by nitrifying bacteria in the plumbing system [99].

NOM emerges as a critical factor influencing nitrification and the efficacy of chloramines. NOM interacts with monochloramine, instigating its decay and releasing free ammonia into the system [100]. This released ammonia is biologically available, serving as a substrate for ammonia-oxidizing bacteria and nitrite-oxidizing bacteria, thereby facilitating nitrification. Even at low concentrations, an increase in NOM concentrations correlates with heightened monochloramine decay, which can further lead to elevated levels of DBPs in the system. Furthermore, the presence of NOM in chloraminated systems enhances the resilience of aerobic bacteria in biofilms to disinfectant residuals, underscoring its role in promoting nitrification [100]. A study by Moradi et al. [101] identified transformative effects in organic compounds during the nitrification process within premise plumbing [101]. The research used fluorescence excitation–emission matrix spectroscopy coupled with parallel factor analysis (FEEM/PARAFAC) to characterize NOM present in both nitrified and non-nitrified waters across varied sampling sites in Australia. The findings reveal a distinct transformation in organic matter composition during nitrification, marked by the emergence of microbial-like compounds, particularly protein-like materials, which are indicative of elevated microbiological activity in the water. This transformation is notably absent in non-nitrified samples, where the organic matter primarily consists of terrestrial humic-like compounds. The study underscores the pivotal role of organic matter as it undergoes compositional alterations, serving as both a substrate and a byproduct of the nitrification process [101].

4. NOM Characterization Techniques

The complexity and variability of NOM presents significant challenges in fully comprehending its characteristics and behaviours in water systems. Figure 1 below provides an overview of the various effects of NOM fractions, highlighting their impact on the formation of DBPs and other influences within the system.

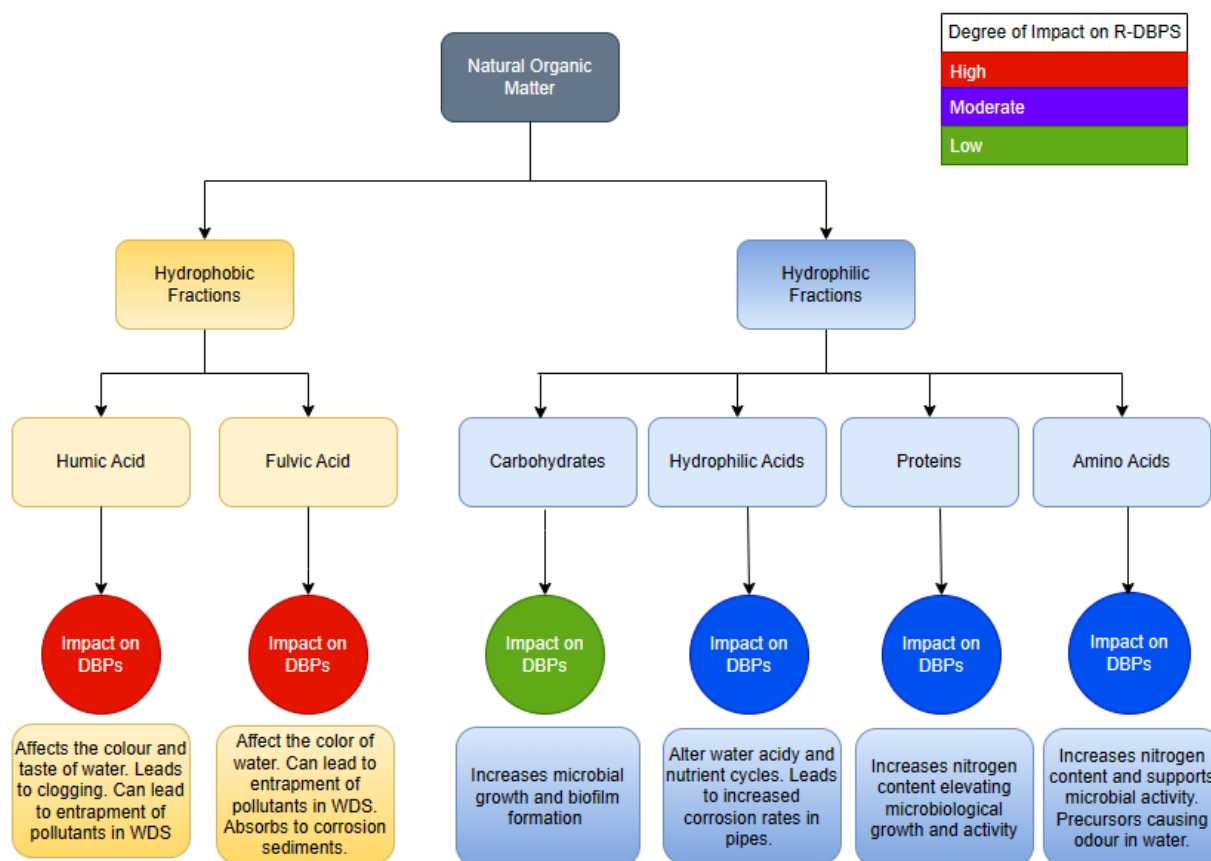


Figure 1. Summary of effects of NOM fractions on water quality in distribution systems.

As such, the use of various characterization techniques to interpret both its functional and structural aspects are needed [102]. There are several existing methods commonly used for high-frequency NOM quantification, including TOC/DOC and UV-light adsorption at specific wavelengths such as 254 nm (UV254) [103]. Despite their quick results, these methods provide overall quantity-related information about NOM, with limited ability to identify sub-groupings or characteristics of the NOM mixture. Other analytical techniques such as fluorescence spectroscopy, Nuclear Magnetic Resonance (NMR) spectroscopy, Size Exclusion Chromatography (SEC), Pyrolysis Gas Chromatography Mass Spectrometry (Py-GC-MS), and Fourier Transform Ion Cyclotron Resonance Mass Spectrometry (FTICR-MS) aim to characterize NOM in more detail. These methods each provide unique insights into NOM characteristics and the relative proportion of sub-groups with similar properties. For instance, fluorescence spectroscopy can reveal information about the aromatic constituents of NOM [104], while high performance size exclusion chromatography qualitatively identifies groupings based on molecular weight [2]. Each characterization method looks to separate sub-groupings based on one or more properties, and therefore there are inherent limitations to each method for fully describing all dimensions of NOM character. The choice of method for better characterization should be based on the specific research goals and available resources, as combining some of these methods may yield in better results [2].

A significant limitation to the majority of NOM characterization techniques is the cost, complexity, and analysis time required. These challenges limit the ability to identify characteristic changes over space and time. However, it is known that the composition and characteristics of NOM are dynamic, subject to alteration by factors like bacterial activity that impact its molecular weight distribution [102]. Previous studies have employed multiple techniques to unravel the significant temporal and spatial variations in NOM characteristics. For example, research in the Florida Everglades employed a variety of methods to highlight the seasonal variability in NOM composition, while studies across various UK rivers employed a diverse set of methods to underscore spatial differences in NOM properties [105,106]. These studies, among others, validate that no single technique can fully capture the multifaceted character of NOM, and that spatial and temporal dynamics in NOM dictate a need for developing novel approaches to NOM characterization. Although these past studies on NOM variability have focused on source waters, the challenge of capturing spatial and temporal dynamics is significant and understudied for WDS. Given long residence times, the impact of microbial activity, pipe material interactions, reactions with disinfectants, and other factors outlined in previous sections, it can be expected that NOM character will vary within a WDS. Although there is a lack of work focused on capturing the extent of NOM dynamics in WDS, recent work by Kurajica et al. [107] demonstrates temporal and spatial variation by fluorescence spectroscopy, including the influence of operating conditions (e.g., flushing) on NOM character. There is more significant indirect evidence based on studies articulating the spatial and temporal dynamics of DBP formation, which would be somewhat correlated with NOM quantity and character [108,109]. Table 1 outlines each technique used for NOM characterization and their advantages and disadvantages, emphasizing the need for a diversified approach to understand and manage NOM in water sources.

Table 1. Summary of NOM characterization techniques applicable in water distribution systems.

Technique	Features	Advantages	Disadvantages
Fluorescence Spectroscopy [2,110]	Excites molecules with specific wavelengths and measures the emitted radiation. Fluorophores produced are used to help outline the structural composition of humic and protein-like materials found in NOM.	Fast, sensitive, and selective. Requires small sample volumes. Does not require sample pre-treatment or pre-treatment is minimal. Potential on-line monitoring.	Sensitive to the environment. Limited to fluorescent components. Interference from other compounds. Complexity of interpretation. Specialized instrumentation and expertise.
Fluorescence Analysis [111]	Peak Picking or Single Point Monitoring: Measures specific wavelength points for fluorescence intensity. Less data-intensive compared to full-spectrum analysis. Spectrum/EEM Analysis: Employs techniques like peak identification, FRI, and chemometric methods to assess water treatment, understand DOM behaviour, and track micropollutants and DBPs	Peak Picking or Single Point Monitoring: Faster measurement times compared to full EEM. Simpler instrumentation. Can be more cost-effective. Suitable for real-time or inline monitoring. Spectrum/EEM Analysis: Enhanced dimensionality and sensitivity. Effective for DOM qualification and quantification. Useful for multivariate analysis.	Peak Picking or Single Point Monitoring: Provides limited information compared to EEM. Can miss some fluorescence features not covered by the chosen wavelengths. Not suitable for complex water matrices where full spectrum information is beneficial. Spectrum/EEM Analysis: Susceptible to weather changes. Limited to fluorescent organic components. Challenges in correlation with parameters. Need for supplementary instruments.
UV-Vis [1]	Measures the absorption of UV and visible light across a spectrum of wavelengths. Identifies the abundance, quality, source, and reactivity of the structural variations of NOM.	Low cost. High sensitivity. Ease of use. Fast measurement times.	Multiple light-absorbing NOM fractions make UV-Vis spectra often indistinct. Other compounds can disrupt measurements.
NMR Spectroscopy [2]	Used to investigate functional groups in NOM. There are different types of NMR techniques (^{13}C NMR, ^1H NMR, ^{15}N NMR, and 2-D NMR) each involving different techniques.	Solid and liquid sample analysis. Different NMR techniques available for structural insights. Multidimensional NMR provides detailed information.	Complexity and heterogeneity of NOM. Technical complexities and cost. Limited quantification capabilities.
Resin Fractionation [5]	Chemical and physical fractionation methods. Resin (Amberlite XAD) and polarity-based techniques. Standardized isolation methods (e.g., IHSS).	Isolates and categorizes NOM. Widely accepted methods. Nuanced separation of components.	Potential NOM alteration due to pH. Irreversible adsorption, resin bleeding. Variable operational conditions affect results.
HPSEC [2,112]	Separates molecules based on their molecular size, where larger molecules elute faster.	Qualitative analysis of NOM. Can provide rough estimate of quantitative analysis when paired with UV-vis. No pre-extraction required. Speed and sensitivity. Availability of equipment.	Influence of eluent choice on outcomes. The adsorption interactions and charge exclusion effects can be controlled by altering the ionic strength and pH of the eluent, which influences the accuracy of results.
Py-GC-MS [2,113]	NOM molecules are disassembled into more analyzable fragments by applying heat under oxygen-depleted conditions. Fragments are then transported into a gas chromatography (GC) column for detection through mass spectrometry (MS).	Disassembles NOM molecules for analysis. Microscale sealed vessel pyrolysis enhances yield. High separation power and sensitivity. Offers structural insights.	Limited to volatile compounds. Complex spectra interpretation challenges.
FTICR-MS [114]	Effectively separates several ions and almost precisely determines molecular formulas. Frequently used in conjunction with other techniques such as Electrospray Ionization (ESI).	Precise molecular formula determination. High mass accuracy and sensitivity. Reveals fragmentation patterns, functional groups, and molecular connectivity.	Expensive and requires technical expertise. Sensitive to contaminants and time-consuming.

4.1. Real-Time or Continuous Monitoring Techniques

Managing distribution systems accurately and optimally throughout the year has been difficult for water utilities due to the complexity of environmental factors, the uncertainty of parameters, and the inability to identify unpredictable scenarios. While many hydraulic and engineering models have been developed to simplify the prediction of water quality

given specific parameters, the difficulty lies in the accuracy of such models in predicting water quality when scenarios and parameters are uncertain. Hence, developing real-time monitoring techniques for water quality is fundamental to optimizing operation and control and reducing labour associated with manual sampling. Water utilities have introduced various online sensors to monitor changes in general parameters such as pH, turbidity, temperature, and conductivity, but have yet to implement monitoring techniques for NOM and their impacts (DBP formation, microbial regrowth, corrosion factors). As such, various spectroscopic techniques mentioned previously have been studied in laboratory-scale settings, but questions remain in terms of their feasibility to be scaled up for universal application in distribution systems.

Moreover, gathering samples is a very constrained process that takes time, depending on the contaminant of interest. Some utilities are often made aware of water quality changes through consumer feedback. A delay between sample analysis and consumer feedback prevents water utility managers from remediating or taking swift action. Some contamination scenarios are often identified days, weeks, or months after their intrusion to the system, such as the Flint water lead crisis in 2014 [115], or fuel contamination of Iqaluit's water supply in 2021 [116]. Short-term contamination can lead to undesirable risks to human health, and thus must be accounted for and monitored at all times. Therefore, implementing real-time monitoring techniques rather than delayed reactivity is vital to ensure proactivity and awareness in such scenarios. Similarly, these techniques must be scaled up to a distribution system and optimally placed to create awareness of unpredictable scenarios. Real-time monitoring technologies, known for their accuracy and sensitivity, are invaluable as they enable prompt and effective response to any changes in water quality within the distribution system.

Offline measurement of NOM spectra might not accurately reflect real conditions, due to potential changes in NOM structure during sample treatment or measurement delay [1]. Therefore, real-time or online measurement is essential to reveal accurate NOM information. Traditional monitoring methods like differential UV absorbance, total organic carbon, and dissolved organic carbon analysis are common approaches used to monitor NOM but have limitations, particularly in detecting only certain types of DBP precursors, such as chromophoric and hydrophobic DBPs [117]. To address these limitations, more sophisticated analytical techniques are required, capable of providing detailed information on dissolved organic matter (DOM) properties, including variations in molecular sizes, structures, hydrophobicity, and chemical composition [110]. Fluorescence and UV differential absorbance spectroscopy have emerged as promising continuous NOM monitoring approaches [2]. In the United States, a method is being employed where samples are fractionated through a fluorescence excitation–emission matrix (EEM) in combination with parallel factor analysis (PARAFAC) [118]. The factors revealed by PARAFAC are then correlated with the total trihalomethane (TTHM) formation potentials, aiding in the identification of specific THM precursors [118]. Additionally, differential UV absorbance (DUVA) can be utilized for real-time estimation of DBP levels in water treatment plants and for managing DBPs in distribution systems [119]. In Australia, real-time monitoring of DBPs is being explored using two online UV spectrometers, offering promising results [120]. Studies have shown that the water source, specifically those with higher organic matter, significantly affects DBP formation and pollutant transport [121].

The potential of spectroscopic monitoring in water distribution systems, particularly for real-time assessment of water quality parameters including DBPs, is significant, yet it comes with certain challenges that need careful consideration. Peak-picking, a straightforward method effective for real-time monitoring, leverages customized sensors based on fluorescence or UV-vis for the online measurement of various water quality indicators [122]. This technique is not only great at monitoring changes in water quality but can also detect process failures through variations in spectral response. Furthermore, when combined with modified Stern–Volmer analysis, peak-picking can trace the quenching of NOM fluorescence due to the presence of heavy metals [123]. However, data generated through

these spectroscopy methods necessitates technical and analytical expertise specifically for the PARAFAC technique, and results can be impacted by environmental variability of water samples [124]. Therefore, while fluorescence and DUVA methods are powerful tools for real-time water quality monitoring, addressing these analytical challenges is crucial for ensuring the accuracy and reliability of the data obtained. Advanced data-processing algorithms, improved sensor technologies, and continuous refinement of the analytical methods are essential to overcome these challenges and fully exploit the potential of fluorescence and DUVA monitoring in water quality management. Future efforts should focus on designing in situ sampling/measuring setups, non-destructive measurements, enhancing instrumental detection sensitivity, and developing software for quicker and simpler analysis [1].

4.2. Characterizing NOM in Multi-Source Networks: Challenges and Opportunities

Multi-source water distribution systems are increasingly recognized for their sustainability, adaptability to fluctuating demands, and enhanced reliability, especially during emergencies. Despite these benefits, multi-source distribution networks present challenges in water quality control monitoring and treatment, as well as coordination between sources. Due to the constant changes, utility managers are often uncertain which water source feeds a specific point within a distribution system.

The variability in NOM characteristics, composition, and type from source to source significantly contributes to challenges in managing water quality in distribution systems that utilize multiple sources. Changes in NOM properties can induce changes in the formation of disinfection by-products, chlorine decay, microbial regrowth, corrosion and scaling, and pollutant transport [125]. Seasonal variability of NOM in one source has already proven to introduce complications in water quality control in distribution systems. The usage of multi-source systems further advances the complication and uncertainty of water quality. Changing the water supply can lead to several adverse effects on drinking water distribution systems [126]. In multi-source water supply networks, like those seen in long-distance water distribution systems, the need for increased chlorination arises due to significant chlorine consumption. This enhanced chlorination, combined with the complexity of water quality from various sources and prolonged hydraulic retention time in the system, potentially leads to a higher formation of undesirable DBPs [121].

In a multi-source WDS with a looped configuration, as studied by Dong et al. [121], key challenges include accurately identifying water sources for different areas using spatial interpolation techniques and achieving precise DBP analysis, which is constrained by the limited number of monitoring points. Compounding this challenge, Weiss et al. [127] noted variations in the types and concentrations of DBPs across different reservoirs. This variability in DBP profiles further complicates the task of managing water quality in such systems, necessitating a more nuanced approach to monitoring and analysis. To address these challenges, future research must focus on investigating NOM sources and characters in reservoirs, employing advanced online monitoring methods like UV254, full UV absorbance scans, and three-dimensional fluorescence [127].

The current state of research concerning the characterization of NOM in multi-source water networks is notably limited, highlighting a significant gap in our understanding of water quality management. The limitations of existing studies, such as the one conducted by Dong et al. [121], underscore the complexities associated with seasonal and spatial variations in multi-source networks. These studies reveal that the characteristics of DBP formation can vary significantly based on the source of the water, the type of distribution system, and numerous other factors. Such variations present a substantial challenge in accurately predicting and managing water quality across different regions and seasons. Future studies should not only aim to fill the existing knowledge gaps but also tailor their methodologies to align with the specific regulations, water sources, and environmental conditions of each region. By focusing on these aspects, research can provide more accurate and region-specific insights, ultimately leading to more effective water quality management

in multi-source networks. This targeted approach in research will not only enhance our understanding of NOM dynamics but also aid in developing more efficient strategies to mitigate the risks associated with DBP formation and other related water quality issues.

5. Conclusions and Future Research Directions

Summarizing the complexities of NOM in water distribution systems, this review underscores the significant challenges posed by residual NOM following water treatment processes. The amount and makeup or character of the NOM entering the distribution system is largely dependent on processes occurring in the source water watershed and the treatment applied. As such, there is significant seasonal variability in NOM composition and behaviour. The diverse chemical compositions and behaviours of NOM necessitate advanced characterization and management strategies to maintain water quality and system integrity. Key issues such as the formation of DBPs, corrosion of infrastructure, and microbial dynamics are closely linked to the presence and variability of NOM characteristics. Furthermore, effective management of NOM is essential to mitigate its impact on water aesthetics, including taste, odour, and colour. In premise plumbing, the interaction of NOM with various pipe materials can lead to heightened corrosion and influence the efficacy of disinfection, posing additional challenges in maintaining water quality at the point of use. Addressing these challenges requires a comprehensive approach that encompasses both the main distribution systems and the intricate dynamics within premise plumbing, ensuring the safety and reliability of water supply from source to tap.

The future of water treatment and distribution management hinges on several key research areas:

1. **Real-Time Monitoring Techniques:** The development of real-time monitoring techniques for NOM in distribution systems is paramount. Current challenges include the high cost and logistical difficulties of implementing advanced spectroscopic techniques in distribution systems. Research should focus on creating affordable, reliable, and universally implementable monitoring instruments;
2. **Characterizing NOM:** An in-depth understanding of NOM's diverse sub-groups and molecular weight variations is critical, especially for high-frequency monitoring that can capture spatial and temporal changes. The development and implementation of cost-effective and scalable NOM characterization techniques are vital to ensure comprehensive spatial coverage within distribution systems. Such monitoring capabilities would enable the timely detection and mitigation of water quality issues related to NOM, facilitating better decision-making in treatment processes and system management. Future research should focus on developing practical and efficient methods for routine NOM monitoring in distribution systems, addressing the dynamic and varied nature of NOM and its impact on water quality;
3. **Addressing Contamination Scenarios:** With the ongoing risks of microbial regrowth and wastewater intrusion, research must continue in developing simulations to predict contamination scenarios and estimate health impacts. Real-time monitoring applications should be valued not just for their accuracy but for their ability to promptly inform water utility managers of changes in water quality;
4. **Scaling Laboratory Techniques:** Innovations in technology should focus on scaling laboratory techniques for efficient and optimal adoption in distribution systems. This includes exploring the seasonal variability of NOM and its interactions within complex water distribution systems;
5. **Impact of Distribution Systems on Water Quality:** The significant alterations in water quality within distribution systems post-treatment call for focused studies and reviews dedicated to these systems. Such research is essential to understand the transformations of NOM and other constituents as water travels through the distribution network. This in-depth exploration would shed light on how these transformations affect the final water quality received by consumers. By delving into the dynamics of water quality changes in distribution systems, we can better identify and address

specific challenges that arise after the treatment process. This knowledge is pivotal in ensuring that water maintains its safety and quality standards to the tap, highlighting the need for continuous monitoring and adaptive management strategies within the distribution framework;

6. Environmental Interactions and Seasonal Variability: The interactions of NOM with the environment, including its seasonal variability, are critical factors affecting water quality. Future studies should explore these interactions in greater detail to enhance our understanding and management of water distribution systems;
7. Enhanced Water Quality Control: The complexity of NOM within distribution systems necessitates a focused approach to water quality control specifically tailored to these environments. Addressing the challenges posed by NOM in distribution systems calls for the development and implementation of innovative technologies and methodologies. These solutions should be designed to efficiently manage the unique properties and behaviours of NOM post-treatment, ensuring that its presence does not adversely affect the quality of the distributed water. Emphasizing control strategies that are effective in the varied scenarios encountered within distribution networks is essential. Such advancements are crucial for maintaining the integrity and reliability of these systems, thereby safeguarding public health and sustaining confidence in the safety and quality of the water supply;
8. Characterizing NOM in Multi-Source Networks: The complexity of managing water quality in multi-source networks, especially considering the variability in NOM characteristics and DBP formation, poses significant challenges. There is a lack of research on this topic; therefore, further research is extremely important to not only improve our understanding of NOM dynamics in multi-source networks but also enhance strategies to manage the associated water quality risks.

Significant progress has been made in understanding and managing NOM in water distribution. However, there remains a critical need for continued research and development in this field. Enhanced monitoring and characterization techniques, coupled with a deeper understanding of NOM's interactions in distribution systems, will be pivotal in ensuring the delivery of safe, high-quality drinking water to consumers.

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