Scientific Contributions Oil & Gas, Vol. 48. No. 2, August: 329 - 345

SCIENTIFIC CONTRIBUTIONS OIL AND GAS
Testing Center for Oil and Gas
LEMIGAS

Journal Homepage:http://www.journal.lemigas.esdm.go.id
ISSN: 2089-3361, e-ISSN: 2541-0520

Comparative Performance Analysis of Natural Fruit Peel Extract and Na_2EDTA As Environmentally Friendly Scale Inhibitors in Tubular Systems

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Manuscript received: May 14th, 2025; Revised: June 06th, 2025
Approved: June 11th, 2025; Available online: June 17th, 2025; Published: June 18 th, 2025.

ABSTRACT - Scale is being found in production tubing and is still being considered a severe operational problem in the oil and gas industry. This is showing the need for scale control using synthetic chemicals such as disodium ethylenediaminetetraacetate (Na_2EDTA), hydrogen chloride (HCL), or hydrogen fluoride (HF). However, concerns about the environmental impact and sustainability of long-term use of synthetic materials are promoting the search for alternatives based on natural materials such as tannin. Therefore, this study is aiming to determine and compare the effectiveness of tannins from rambutan binjai (Nephelium lappaceum), rambutan nona (Nephelium mutabile), and mangosteen (Garcinia mangostana) peel extract as natural scale inhibitors against Na2EDTA performance. To achieve the objective, UV-Vis spectrophotometric analysis is being carried out and is showing tannin containing 20.91% (rambutan binjai peel), 21.14% (rambutan nona peel), and 21.58% (mangosteen peel). Laboratory tests are being conducted with variations in tannin volume (5 mL, 10 mL, and 15 mL) as well as soaking times of 20 and 60 minutes in 20 mL distilled water. The results are showing that the increase in tannin volume addition and soaking duration is being positively correlated with the decrease in scale mass. The highest performance is being shown by mangosteen peel extract, which is reducing scale by 0.132 grams (6.6%) at 15 mL in 60 minutes. For comparison, Na_2EDTA under the same conditions is reducing 0.176 grams (8.8%). These results are showing the potential of tannin-rich fruit peel extract as an environmentally friendly and sustainable scale inhibitor alternative for oil and gas production systems.

Keywords: scale, inhibitors, rambutan peel, mangosteen peel, Na_2EDTA.

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How to cite this article:

Novrianti, Taufiq Hidayat, Neneng Purnamawati, and M. Ridha Fikri, 2025, Comparative Performance Analysis of Natural Fruit Peel Extract and Na_2edta As Environmentally Friendly Scale Inhibitors in Tubular Systems, Scientific Contributions Oil and Gas, 48 (2) pp. 329-345. DOI org/10.29017/scog.v48i2.1813.

INTRODUCTION

The inorganic scale is often a problem in oil and gas production systems, where the deposition occurs in wellbore tubing and flowlines. The formation of scale, such as calcium sulfate, has long been recognised as one of the serious problems in oil and gas production, leading to reduced production rates as flow becomes restricted.(Poernomo & Makmur 2004) The accumulation of inorganic scale is often on the inner surfaces of the walls and narrows the cross-sectional areas. In extreme cases, the pipelines are choked completely, thereby hindering operational efficiency, which leads to financial loss for the business (Macedo et al. 2019). The main components of scale include calcium carbonate ($CaCO_3$), gypsum ($CaSO4_2H_2O$), and barium sulfate ($BarS0_4$), while other compounds are strontium sulfate ($SrSO_4$), calcium sulfate ($CaSO_4$), and iron-containing compounds, specifically iron carbonate ($FeCO_3$), iron sulfide (FeS), and iron oxide (Fe_2O_3). To reverse the challenges, several mitigation methods have been considered, including mechanical removal, well acidizing (Shams El Din et al. 2002), and physical methods that comprise electronic descaling, ozonation, and electrostatic methods. Long-term use of chemical inhibition and the addition of a disperser are two of these alternatives, which are most viable and effective due to deployment and stable performance. Recently, synthetic inhibitors such as sodium carboxymethyl cellulose (Chaussemier et al. 2015), compositions (polymeric) that work by targeting hydroxyapatite, or green polymers responsive to the environment, have been the focus of several studies due to the potential preventative ability (Popuri et al. 2014).

In oil and gas production, particularly in systems where ions of divalent and trivalent metals are present in large numbers, the formation of inorganic scale is a significant issue that imposes a limitation on operations. Among all available chemical methods, ethylenediaminetetraacetic acid disodium zeolite (Na_2EDTA) is the most preferred due to high efficiency. Sodium salt of the synthetic aminopolycarboxylic acid ethylenediaminetetraacetic acid Na_2EDTA is well recognized as a potent complexing agent that can form stable complexes with various metal ions like Ca^{+2}, Mg $^{+2}$, Fe^{+2} Fe^{+2}, Sr^{+2}, and Ba^{+2}. These characteristics have made Na_2EDTA a basis of industrial water treatment, archaeology preservation, and, most importantly, in the oil fields.

The effectiveness of Na_2EDTA in purging and binding ions that form scale is well documented. It inhibits reprecipitation of standard oilfield scale, such as calcium carbonate, calcium sulfate, and strontium sulfate (Moghadasi et al., 2007; Onojake & Waka, 2021). The performance is specific in brine system thermodynamics as well as industry high-salinity and high-temperature reservoirs, which enhance scaling propensity due to reservoir thermodynamics and kinetics. Na_2EDTA has been applied in operational practice concerning scale retarding, keeping the pipelines fluent, and ensuring continuity of production through complexing of scaling ions (Onojake & Waka 2021). For example, in an oilfield called Rumaila, Na_2EDTA dissolved calcium sulfate plugs in electric submersible pumps. This helped address the plugging problem and produced higher efficiency (Ren et al. 2018).

In numerous industrial and environmental applications, Na_2EDTA has been the tool of preference regarding descaling and scale prevention due to flexibility of usage during operation and the stability of performance (Husna et al. 2022). Besides allowing advanced maintenance scheduling, this chemical prevents repetitive well shut-ins, which will help minimize productivity loss and cut down related operational costs (Gamal et al. 2020). Compared to other traditional inhibitors available, Na_2EDTA can be viewed as an environmentally friendly solution to pollution. This is because previously used inhibitors are non-biodegradable, posing a hazardous character (Ganguly et al. 2023).

Regardless of the commonly accepted benefits, environmental issues exist with Na_2EDTA. Despite the relative economic benefits and substantial biodegradation, the duration of ecological persistence and proclivity to spurn heavy metals and increased mobility raise significant concern in the ecology department. Therefore, the application and discarding of Na_2EDTA in field operations must be considered, following special regulatory supervision. This concern has increased interest in designing biodegradable and natural scale inhibitors, particularly biopolymers and other non-toxic materials (Almubarak et al. 2022).

Refractory scale-forming ion depletion and the related increase in scale formation in water distribution systems have been the focus and concern of the scientific and engineering community over the years. Recent studies have been focused on searching for environmentally friendly alternatives that can achieve the same scale inhibition efficacy better or in identical manner. Some potential candidates include natural polyphenolic compounds from plant sources, specifically tannin, whose actual substances are derived from agricultural waste.

Polyphenolic tannin is a family of naturally occurring substances that has gained popularity in the oil and gas industry as a potential green scale inhibitor. The compound structure of tannin, with extensive hydroxyl and aromatic groups, facilitates the formation of complexes with divalent and multivalent ions (mainly Ca^{2+}, Mg^{2+}, and Fe^{3+}). It prevents the setting up of mineral scale, which causes obstruction of fluid passage and reduced effectiveness of equipment.

Tannin is defined as a subdivision of the polyphenol family. This is because the strong metal-chelating and anti-crystal forming properties possess the unique characteristic useful in environmentally friendly scale-inhibition applications, specifically in ecologically concerned processes (Khormali et al. 2014). However, tannin can disrupt crystal nucleation and growth, decrease scale adhesion, and interfere with the growth of pre-formed crystalline deposits by forming stable complexes with the metal ions. The mechanisms are used in various industries where metal ions cause scale application, such as oil production and water treatment (Sergio et al. 2016; Sesia et al. 2023). Due to polyphenolic constitution, tannin is declared to possess chelating capabilities. This allows for a decrease in scale formation because of stabilization effects on immediate ions as well as inhibiting nucleation and crystal development (Sesia et al. 2023). Furthermore, tannin is non-toxic, biodegradable, and derived from renewable sources, signifying a new option to artificial scale control reagents (Sergio. et al. 2016; Sesia et al. 2023). The addition of tannin to water treatment practice is related to the industrial trend of recent green chemistry and the search for environmentally sustainable and friendly practices.

In recent studies, tannin offers benefits beyond scale mitigation, including modifications to the rheological and filtration properties of water-based drilling systems when exposed to high temperatures. The properties allow for the optimization of drilling fluids functionality in hot drilling conditions (Ismail et al. 2020). This dual property manifests the diversionary capacity of tannin to be disseminated in usefulness in drilling fluid system. Despite the growing environmental awareness about the issue of chemical pollutants and associated concerns on the health of humanity, there has been a greater interest in the world of academia in natural polyphenolic compounds, specifically those obtained from biomass and agricultural waste in the form of tannins. These entities are a potential template for the drug design of the next generations of inhibitors that further bring the concepts of green chemistry and sustainability. Recent studies have proven that biomass rich in polyphenols possesses strong adsorption and protective properties on the metal surface.

Table 1. Tannin content of fruit peel

Fruit/ Fruit Peel	Tannin Content (% dry weight)	References
Pomegranate Peel	20%- 26%	(Lado et al. 2020; Nazzal & Hariri 2010)
Mangosteen Peel	12% - 18%	(Hafid et al. 2016)
Rambutan Peel	10% –15%	(Panzella & Napolitano 2022)
Grape Seed	13% –18%	(Panzella & Napolitano 2022)
Banana Peel	6% –12%	(Panzella & Napolitano 2022)
Cashew Apple	6% –10%	(Liang & Yi 2009)
Guava Leaf / Peel	8% –12%	(Fraga-corral et al. 2021)
Tamarind Pulp	5% –8%	(Liang & Yi 2009)
Persimmon Fruit	7% –13%	(SaThierbach et al. 2015)
Blackberry Fruit	5% –7%	(Sonya 2020)

This makes polyphenols more supportive as corrosion inhibitors in acidic environments, with environmental sustainability. Furthermore, black tea waste has been reported to show high inhibition and protective effects, confirming a prospective green corrosion control agent to be used in the industrial sector (Wulandari et al. 2023).

Chelating capacity and industrial usability can be significantly influenced by the variable composition of tannin that depends on the source of plant origin. Therefore, characterization and standardization are essential elements in achieving reproducible performance to allow widespread application of tannin (Zhen et al. 2021). Table 1 presents tannin content of various fruits and peel, which are commonly investigated as raw materials for natural extraction. Based on Table 1, mangosteen and rambutan peel have a high content of bioactive chemicals, such as tannin, terpenoids, polyphenols, steroids, flavonoids, and saponins. The two-skinned fruit plants are grown in Indonesia, specifically in Riau Province. Rambutan Binjai and Nona are the most effective species of the rambutan genus, with a production of 21,973 and 40,510 tons in 2020 and 2021, respectively. Additionally, Riau province is one of Indonesia's top 10 largest mangosteen-producing provinces, namely 6,977 tons, according to the Central Statistics Agency. Currently, rambutan binjai, rambutan nona, and mangosteen fruit peel has not been optimally used by the community, as the majority is being discarded as waste. According to (Sugihardjo 2020), applying environmentally friendly inhibitors derived from natural materials has shown significant potential in reducing scale deposition while minimizing environmental risks in oil and gas production systems. (Darwita 2010) emphasized that tannin-based inhibitors, extracted from various natural sources, can effectively reduce scale formation by chelating metal ions, thereby preventing crystal growth in oilfield systems.

Based on the description above, this study aimed to analyze the effect of tannin extract in rambutan and mangosteen peel on the success in scale reduction. The variation of tannin concentration of rambutan binjai, rambutan nona, and mangosteen peel extract, as well as soaking time, was examined to analyze the effectiveness on scale reduction. The results of this test were compared with the analysis conducted on Na_2EDTA using the same concentration and soaking time variations. This determines which scale inhibitor reduces scale between NA_2EDTA and tannin from rambutan and mangosteen peel extract. The information obtained is expected to contribute to developing sustainable and locally sourced scale inhibitors for use in oil and gas production systems. According to a study carried out by Akhdan et al. (2022), the use of natural materials, particularly agricultural waste, provides substantial benefits in all aspects of environmental safety, economic potential, and biodegradation. This makes natural materials a highly competitive alternative to the common chemical inhibitor in oilfields.

METHODOLOGY

The preparation of materials and equipment was carried out before the experimental procedures. Instruments used in this study included a digital analytical balance (ACIS Electronic Price Computing Scale), blender, laboratory oven (nabertherm oven), measuring cylinder, 100-mesh sieve, rotary evaporator (yamato rotary evaporator), and a stopwatch (analog stainless watch). The main ingredients consisted of rambutan nona, rambutan binjai, and mangosteen peel, which was obtained and collected from the waste contained in the Pahlawan pop-up market, Perum Sidomulyo pop-up Market, Nurul Amal pop-up Market, Marpoyan Pekanbaru, and Tanah Merah pop-up Market Kampar. Inorganic scale samples were from a production flowline located in Field X. Approximately 96% of the ethanol and Na_2EDTA solution for analytical laboratory was purchased at the store Putra Marwa Perkasa located at HR Subrantas Panam Pekanbaru.

Figure 2. Nona rambutan peel

Figure 1. Binjai rambutan peel

Figure 3. Mangosteen peel

Tannin extraction used in this study included the application of a standard laboratory procedure, an adapted form of phenolic extraction methodology established in the literature (Sun et al. 2012; Wong et al. 2024). Initially, peel samples were washed using distilled water to remove any impurities and continuously air-dried at room temperature on a five-day basis to promote maximum dehydration. This drying step was essential for three interrelated reasons, namely to reduce the moisture level, hinder the growth of microorganisms, and maintain the stability of thermolabile phenolic compounds (Thinkratok et al. 2014). After drying, peel was ground into a fine powder using a laboratory blender. The material obtained was sieved to a uniform particle size using a 100-mesh sieve, ensuring consistent surface area exposure for effective extraction. Approximately 350 grams of powdered peel was subjected to maceration using 96% ethanol, with a solid-to-solvent ratio of 1:3 (b/v). The mixture was stirred and left to stand at room temperature for 72 hours to allow sufficient contact time for tannin dissolution into the solvent phase (Sun et al. 2012). After the maceration process, the solution was filtered using the Whatman No. 1 filter paper to separate the solid parts that remained in the liquid extract. The ethanol filtrate was then dried under a rotary evaporator at low pressure (36 °C, 90 rpm) to give a very viscous crude extract enriched with tannin. The method was reported to be effective in extracting phenolic fractions with high antioxidant activity from tropical fruit peel. This showed potential application for carrying out a study in food science, pharmaceutical science, and cosmetic science (Wong et al. 2024).

The experimental procedures included immersing pre-weighed inorganic scale samples in test solutions containing rambutan binjai, rambutan nona, mangosteen peel extract, or Na_2EDTA, which served as the synthetic control inhibitor. Each inhibitor was tested at three volume concentrations, namely 5 mL, 10 mL, and 15 mL, diluted in 20 mL of distilled water. Soaking duration was set at 20 minutes and 60 minutes, respectively. After the immersion process, the samples were dried and reweighed to determine the change in mass. The inhibition efficiency was calculated based on the difference in weight before and after treatment, representing the amount of scale dissolved.

Table 2. Sample for soaking time of 20 minutes

Inhibitor Type	Volume (mL)
Rambutan Binjai Peel Extract	5
Rambutan Binjai Peel Extract	10
Rambutan Binjai Peel Extract	15
Rambutan Nona Peel Extract	5
Rambutan Nona Peel Extract	10

Rambutan Nona Peel Extract	15
Mangosteen Peel Extract	5
Mangosteen Peel Extract	10
Mangosteen Peel Extract	15
Na_2EDTA	5
Na_2EDTA	10
Na_2EDTA	15

Table 3. Sample for soaking time of 60 minutes

Inhibitor Type	Volume (mL)
Rambutan Binjai Peel Extract	5
Rambutan Binjai Peel Extract	10
Rambutan Binjai Peel Extract	15
Rambutan Nona Peel Extract	5
Rambutan Nona Peel Extract	10
Rambutan Nona Peel Extract	15
Mangosteen Peel Extract	5
Mangosteen Peel Extract	10
Mangosteen Peel Extract	15
Na_2EDTA	5
Na_2EDTA	10
Na_2EDTA	15

RESULT AND DISCUSSION

Characterization of tannin compounds in rambutan nona, rambutan binjai, and mangosteen peel extract.

To determine the percentage of tannic acid content in each sample, analysis was carried out using a UV-Visible spectrophotometer. (spectrophotometer UV – Vis) The spectrophotometric testing procedure was conducted directly by the Testing Laboratory of BPSIP Riau. The measured percentages of tannic acid present in rambutan nona, rambutan binjai, and mangosteen peel extract are presented in Table 4.

Table 4. Percentage of tannic compounds in Binjai Rambutan, Nona Rambutan, and Mangosteen Peel Extract

Test Parameter	Organic Acid Source	Result (%)	Method
Tannin Content	Binjai Rambutan Peel	20.91	UV-Vis Spectrophotometry
	Rambutan Nona Peel	21.14	
	Mangosteen Peel	21.58	

Table 4 shows the tannic concentrations obtained by UV-Visible spectrophotometry with extract prepared using rambutan binjai, rambutan nona, and mangosteen peel. However, the three extracts had duplicate high tannin content, ranging between 20.91 % and 21.58 %. The most concentrated with tannin content was mangosteen of 21.58 %, rambutan nona (21.14 %), and rambutan binjai extract (20.91 %).

The current observations show that all of the investigated extracts have scale-inhibition effect. This is also observed in the case of the well-known chelating properties of tannin, allowing the binding of metal ions associated with scale formation. Inter-sample variation in tannin concentration was relatively small. However, this disparity could be explained by cultivar type, growth conditions, and state of fruit maturity at harvest time. Because all samples contained tannin contents of more than 20 % tannin, this shows potential rich sources of polyphenolics. Additionally, mangosteen extract in the highest proportion of tannin can prove even better at scale mitigation.

Composition of scale

Scale sample used in this study was collected from a production flowline located in Field X. The chemical composition was characterized using X-ray fluorescence (XRF) spectrometry (Rigaku Supermini 200).

Table 5 summarizes the chemical analysis of scale sample collected in a flowline in Field X, through XRF spectroscopy. Calcium (Ca) has the highest overall percentage of 90.96 %, followed by iron (Fe), 3.449 %, and strontium (Sr), 3.138 %. Other traces have silver (Ag), manganese (Mn), silicon (Si), and zinc (Zn).

The high calcium level shows that the percentage of calcium carbonate ($CaCO_3$) is significant in scale formation, which is quite common when oil and gas production systems are located in hard water areas and protracted temperature and pressure environments (Kan & Tomson 2012). Although it occurs in relatively low concentrations, the presence of strontium and barium should be noted because of the tendency to combine readily and form highly insoluble compounds like strontium sulfate ($SrSO_4$) and barium sulfate ($BaSO_4$). These compounds have been reported to cause severe scale deposition.

Analysis of pH in Rambutan Binjai, Rambutan Nona, and Mangosteen Peel.

Table 6. pH Values of various Inhibitors

Type of Scale Inhibitor	pH Value
Organic acid from Binjai rambutan peel extract	5.23
Organic acid from Nona rambutan peel extract	5.14
Organic acid from mangosteen peel extract	5.77
Na_2EDTA (Ethylenediaminetetraacetic acid disodium salt)	5.54

Table 6 shows pH measurements of four scale inhibitors tested. Among the natural extract, the organic acid of mangosteen peel showed the maximum pH value of 5.77, followed by rambutan binjai, rambutan nona, and Na_2EDTA at 5.23, 5.14, and 5.54, respectively. All tested inhibitors are mildly acidic, which is good for the potential inhibition of scaling in oilfield systems. Acidic media favor the protonation of active sites of polyphenolic compounds like tannin and flavonoids with high chelating capacity, serving as scale inhibitors. Similarly, Makmur (2022) showed that the effectiveness of scale inhibitors increased with pH. This was because more of the inhibitor molecules could be adsorbed onto scale crystals, as showed by SEM. (Collins et al. 2021) also established that pH played a determinative role regarding the effectiveness of scale inhibitors. However, inorganic amine-based inhibitors are not effective at low pH values and work significantly better when the temperature is elevated and pH is close to neutral.

Extraction parameters have a significant impact on regulating the overall pH value and plant-based scale inhibitors. For example, ethanol processes with maceration and ultrasound-assisted extraction produce varied levels of phenolic and flavonoid constructs, which inevitably alter the acidity achieved in final extract (Plaza et al. 2021). Solvents that are acidified with citric or acetic acids can also increase the solubility of anthocyanins and polyphenols, allowing a change in pH profile of extract (Aparna & Lekshmi 2023). Therefore, the selection of solvent system, extraction temperature, and duration is still critical in managing the best chemical traits of natural scale inhibitors, particularly pH (Achmad et al. 2022)

Previous studies have shown that the acidic nature of scale inhibitors significantly influences the dissolution of alkaline earth metal scale such as calcium carbonate and calcium sulfate. According to (Baraka-Lokmane & Sorbie 2010), inhibitors of slightly acidic pH (4-6) have higher potential in terms of nuclei destabilizers strength and enhancing solubility of the deposited salts through proton-mediated ion-exchange reactions. The pH of scale inhibitors is a major determinant of their performance. This is because lower pH causes greater mobility of hydrogen ions, reactivity, higher scale inhibitor complexes with chelating agents, and a faster descaling reaction.

Na_2EDTA is a well-known chelating agent with consistent performance across various pH levels and competitive acidity profiles. The slightly lower pH values of the rambutan-based extracts suggest a higher concentration of free carboxylic or phenolic groups, which can enhance complexation with scale-forming ions such as Ca^{2+} or Ba^{2+}.

Based on the results, pH measurements support the suitability of fruit peel extract as environmentally friendly scale inhibitors. The acidity levels also contribute to the functional effectiveness in disrupting inorganic crystal growth in the petroleum production environment.

Effectiveness of Rambutan Binjai peel extract as an organic scale inhibitor

The experimental results presented in Figure 4 show a correlation between inhibitor volume, soaking duration, and scale inhibition performance using rambutan Binjai peel extract. At an immersion time of 20 minutes, the percentage of weight reduction increased significantly from 2.25% at 5 mL to 3.75% at 15 mL. Although the inhibition efficiency at this stage was moderate, there was an indication of early-phase activity of the bioactive compounds, with limited contact time. At 60 minutes of immersion, the inhibition efficiency was significantly enhanced, increasing from 3.45% to 4.30% as inhibitor volume rose from 5 mL to 15 mL. This improvement was attributed to the prolonged interaction between the tannin-rich extract and scale-forming ions on the sample surface. The extended contact period facilitates better adsorption and chelation, leading to more effective disruption of crystal nucleation and growth processes.

The results correlate with previous studies, showing that the efficiency of natural polyphenolic inhibitors is influenced by both concentration and contact time. For instance, a study on modified valonia tannin extract showed that increased dosages and reaction time enhanced the anti-scale performance against calcium carbonate by interfering with crystal growth through chelation and dispersion mechanisms (He et al. 2023). In addition to the volume and duration effects, the acidic nature of extract (pH 5.23) contributed to its performance. Mildly acidic conditions are known to enhance chelating ability of polyphenolic compounds such as tannin by increasing proton availability, which supports stronger interactions with divalent and trivalent metal ions (e.g., Ca^{2+}, Ba^{2+}, Fe^{3+}). The pH level of rambutan binjai extract within the favorable range for metal ion complexation can improve the capacity to disrupt the precipitation of scale-forming salts.

The chelating abilities of plant polyphenols have been well-documented, with studies showing the capacity to bind metal ions due to structural features like hydroxyl and carboxyl groups. This property is crucial in preventing scale formation by stabilizing metal ions in solution and inhibiting the participation in crystal growth (Scarano et al. 2023).

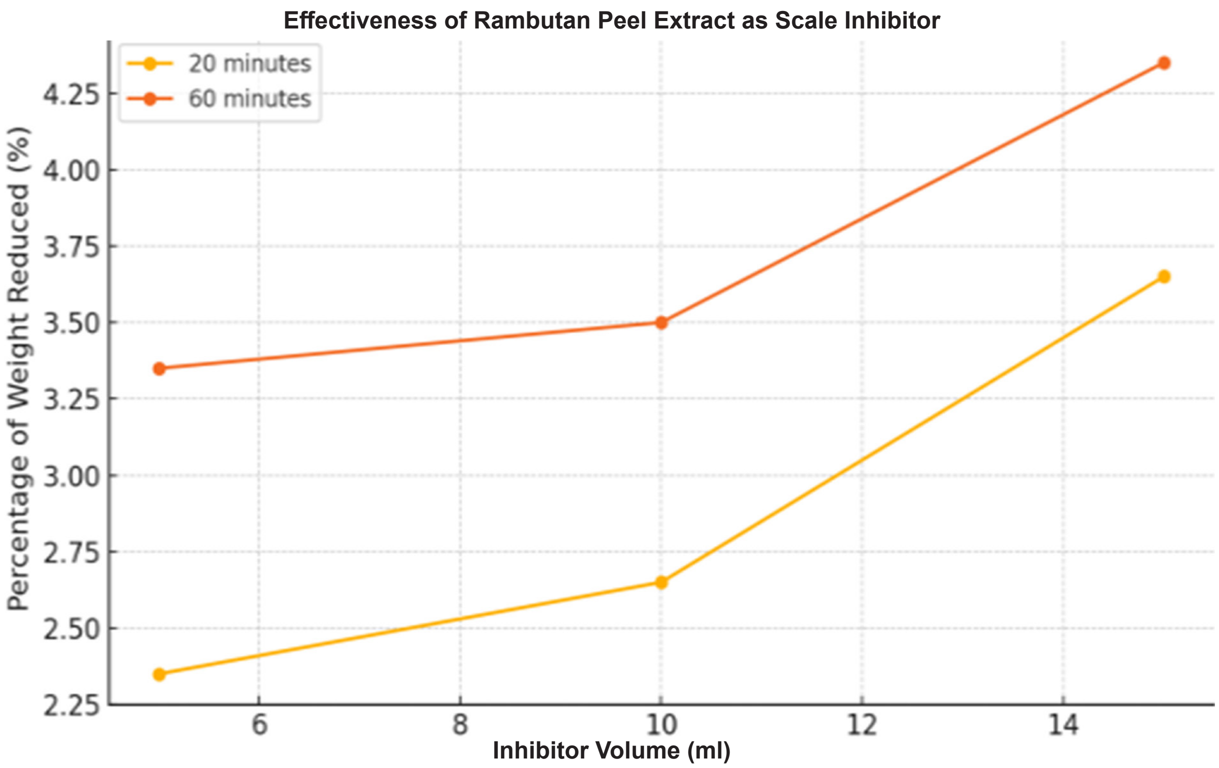

Figure 4. Effectiveness Of Rambutan Binjai peel extract as an organic scale inhibitor

Effectiveness of Rambutan Nona peel extract as an organic scale inhibitor

As shown in Figure 5, the experimental results were differentiated to affirm that the volume of inhibitor, soaking time, and scale inhibition efficacy of rambutan nona peel extract were differentiable in a mean or linear correlation pattern. After 20 minutes of immersion, the percentage weight loss increased gradually with values of 2.25% at 5 mL to 3.75% at 15 mL. Although the inhibitory activity at this stage was moderate, the result still showed that the bioactive constituents were active immediately despite the low contact time.

At steady-state, a 60 to 120-minute increase in immersion time was observed to record a rise in inhibition efficiency, recorded at 3.45 to 4.30% moving the volume of the inhibitor from 5 mL to 15 mL. This is explained by the long duration of the contact between tannin-rich extract and scale-forming ions that are adsorbed on the surface of test material. The extended interaction has more beneficial adsorption and chelation properties, which disrupt the nucleation and growth of crystals (He et al. 2023).

The current data confirms previous results, where concentration and contact time affect the efficacy of natural polyphenolic inhibitors. Based on experimental data using modified valonia tannin extracts, a greater effect on calcium carbonate anti-scale properties is observed with increased dosage and reaction time. This is because the treatment inhibits calcium carbonate crystal growth through chelation and dispersion processes (He et al. 2023).

In addition to the volume and duration effects, the acidic nature of extract (pH 5.23) contributed to its performance. Mildly acidic conditions are known to enhance the chelating ability of polyphenolic compounds such as tannins by increasing proton availability, which supports stronger interactions with divalent and trivalent metal ions (e.g., Ca^{2+}, Ba^{2+}, Fe^{3+}) (Babula et al. 2021). The pH level of rambutan Binjai extract in a favorable range for metal ion complexation can contribute to improved capacity to disrupt the precipitation of scale-forming salts.

Chelating ability of plant polyphenols has been well-documented, with studies showing the capacity to bind metal ions due to structural features like hydroxyl and carboxyl groups (Olennikov et al. 2014). This property is crucial in preventing scale formation by stabilizing metal ions in solution and inhibiting the participation in crystal growth.

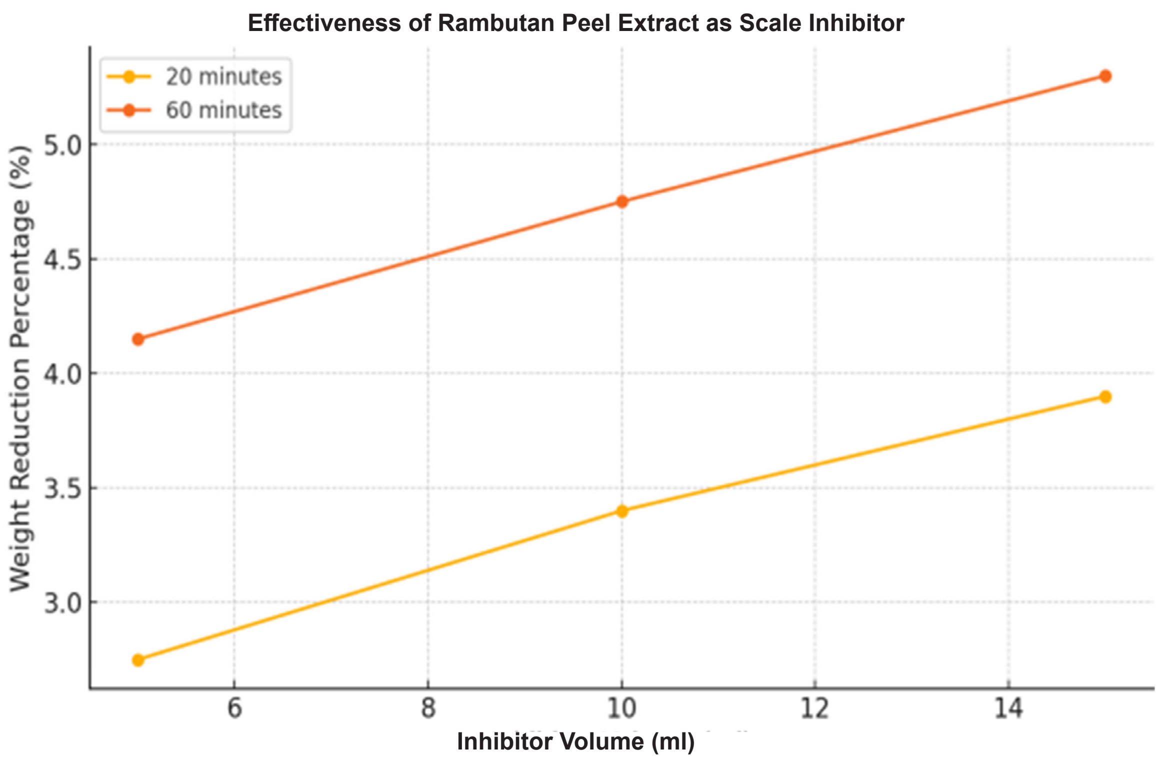

Figure 5. Effectiveness of Rambutan Nona peel extract as an organic scale inhibitor

Effectiveness of mangosteen peel extract as an organic scale inhibitor

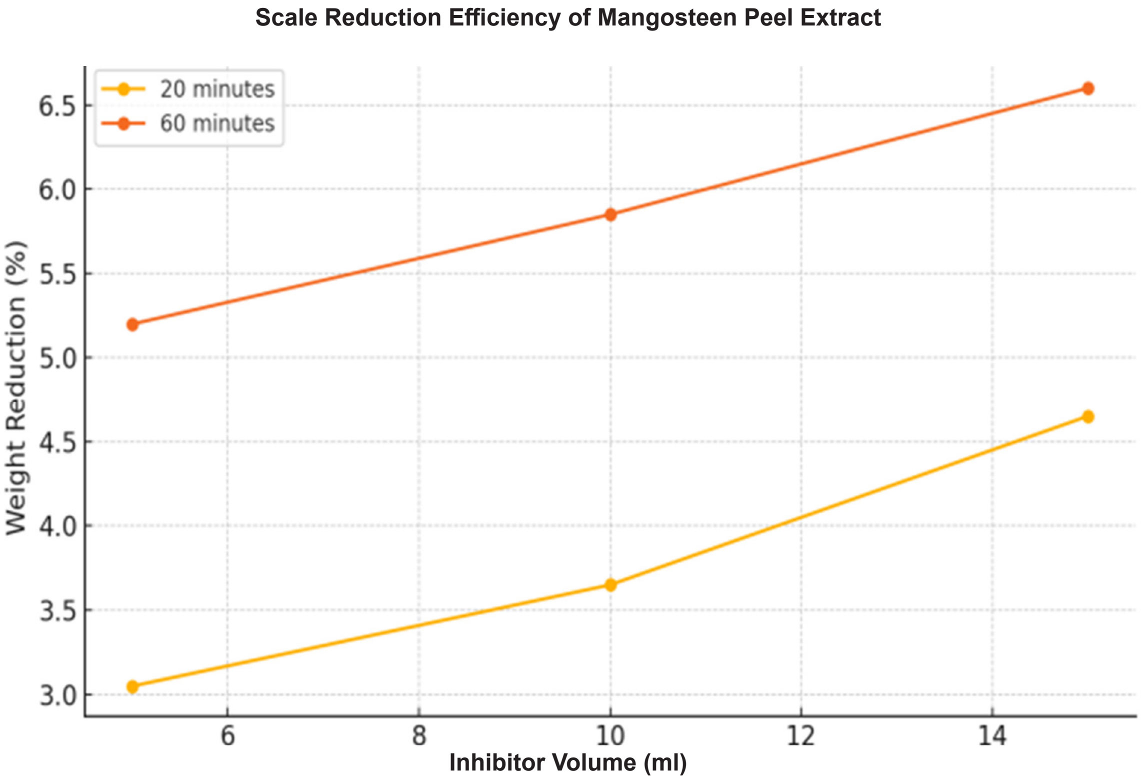

Figure 6. Effectiveness of mangosteen peel extract as an organic scale inhibitor

An empirical study on the effectiveness of mangosteen peel extract as scale inhibitor was conducted. The results showed that a statistically significant association existed between the volume of extract and the increase in duration of exposure, to a decrease in the percentage reduction of scale mass. Specifically, weight loss was higher after a 20-minute immersion (3.05 % with 5 mL and 4.65 % with 15 mL), showing that extract had the initial power to improve scale deposit after a relatively short contact time.

The results are in line with previous studies carried out on plant-derived scale inhibitors. Khamis et al. (2024) showed that natural extract like rosemary possessed high scale-inhibition potential due to the functional groups with the ability to chelate cations and inhibit the formation of crystalline structures

Effectiveness of Na_2EDTA as scale inhibitor

Experimental results in Figure 7 show that scale-prevention ability of Na_2EDTA increases both with the volume of the solution and the immersion time. The percent weight reduction trend increases steadily with rising volume of Na_2EDTA to 20 minutes, reaching 7.00% and 8.80% at 5 mL and 15 mL, respectively. This shows that Na_2EDTA at a relatively short contact time of 20 minutes can interact with scale-forming cations by surface complexation or initial chelation. The effect becomes stronger at 60 minutes, where scale mass decreases by 4.40 % and 5.35% at 5 mL and 15 mL, respectively. Despite the overall reduced percentage, the steady ratcheting-up of the percentage as the volume increases supports the theory that more prolonged contact improves probability of stable complexes of Na_2EDTA with divalent ions like Ca^{2+} and Mg^{2+}. This effect can be explained by kinetic forces, such as diffusion into micro-porous layers of scale, and duplication of molecular tropism.

The results are consistent with the reported time-dependent behavior of green and synthetic inhibitors. For example, Jafar Mazumder (2020) and Ituen et al. (2017) reported that growth in the efficiency of inhibitors could be explained as primarily due to high molecular adsorption and ion binding at the solid-liquid interface. Other studies by Onoghwarite & Endurance, (2019) suggested that longer contacts promoted more substantial surface covering, thereby obstructing scale development.

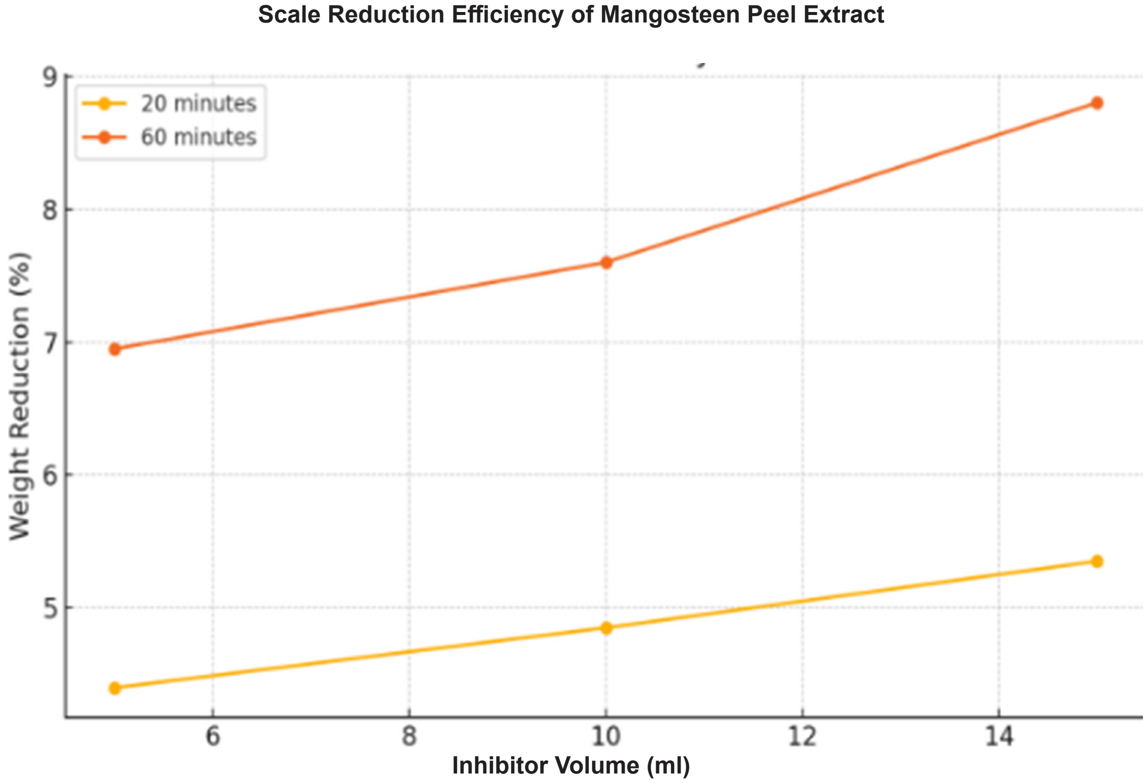

Figure 7. Effectiveness of Na_2EDTA as an scale inhibitor.

Comparative study of scale inhibition efficiency: natural extract vs. Na_2EDTA at soaking time 20 minutes

Scale formation in oil and gas industry is a common phenomenon that must be addressed with appropriate intervention measures. To determine the effectiveness of four potential scale inhibitors, namely rambutan Binjai, rambutan nona, mangosteen peel extract, and Na_2EDTA, three different concentration levels (5 mL, 10 mL, and 15 mL) and a constant soaking time (20 min) were used as part of the experiment. A strong positive relationship between dosage magnitude and the percentage of phosphorus-scale mass reduction was found in all inhibitors. Mangosteen peel recorded the highest inhibition efficacy, with a 15 mL dosage showing maximum weight decrease of 4.05%. This value was higher compared to rambutan nona peel (3.90%) and rambutan Binjai peel (3.65 %), which were conducted under the same conditions. The high efficacy of mangosteen can probably be explained by the more abundant content of phenolic compounds and xanthones, which possess a high chelating activity and the ability to bind cations, leading to scale formation (Mazumder 2020)

The synthetic chelating agent, Na2EDTA, was more effective in the calcite scale inhibition, as the maximum concentration achieved a 5.35 % scale reduction. The performance has been observed to be more effective than the other inhibitors. This is because of the ability to form stable complexes with divalent metal ions of Ca^{+2} and Mg^{+2}, which hinders the process of nucleation and growth of scale.

Based on the results, pH of individual inhibitors was proven to be an important parameter in chelation efficiency. The pH of measured values was 5.23 (Binjai rambutan peel), 5.14 (Nona rambutan peel), 5.77 (Mangosteen peel), and 5.54 (Na_2EDTA). This higher pH of mangosteen extract presents more favorable binding conditions by decreasing competition with protons at active sites, promoting stronger interactions between metal and ligand (Khormali & Petrakov 2016). However, the complex might not form under a more acidic condition, like rambutan nona extract, because of the abundant concentration of hydrogen ions. Na_2EDTA remained highly efficient even at a relatively acidic pH of 5.54. These results show the strong chelating ability of Na_2EDTA, which can be used under a wide range of pH and is applicable in industrial applications for the control of scale produced by various operational conditions.

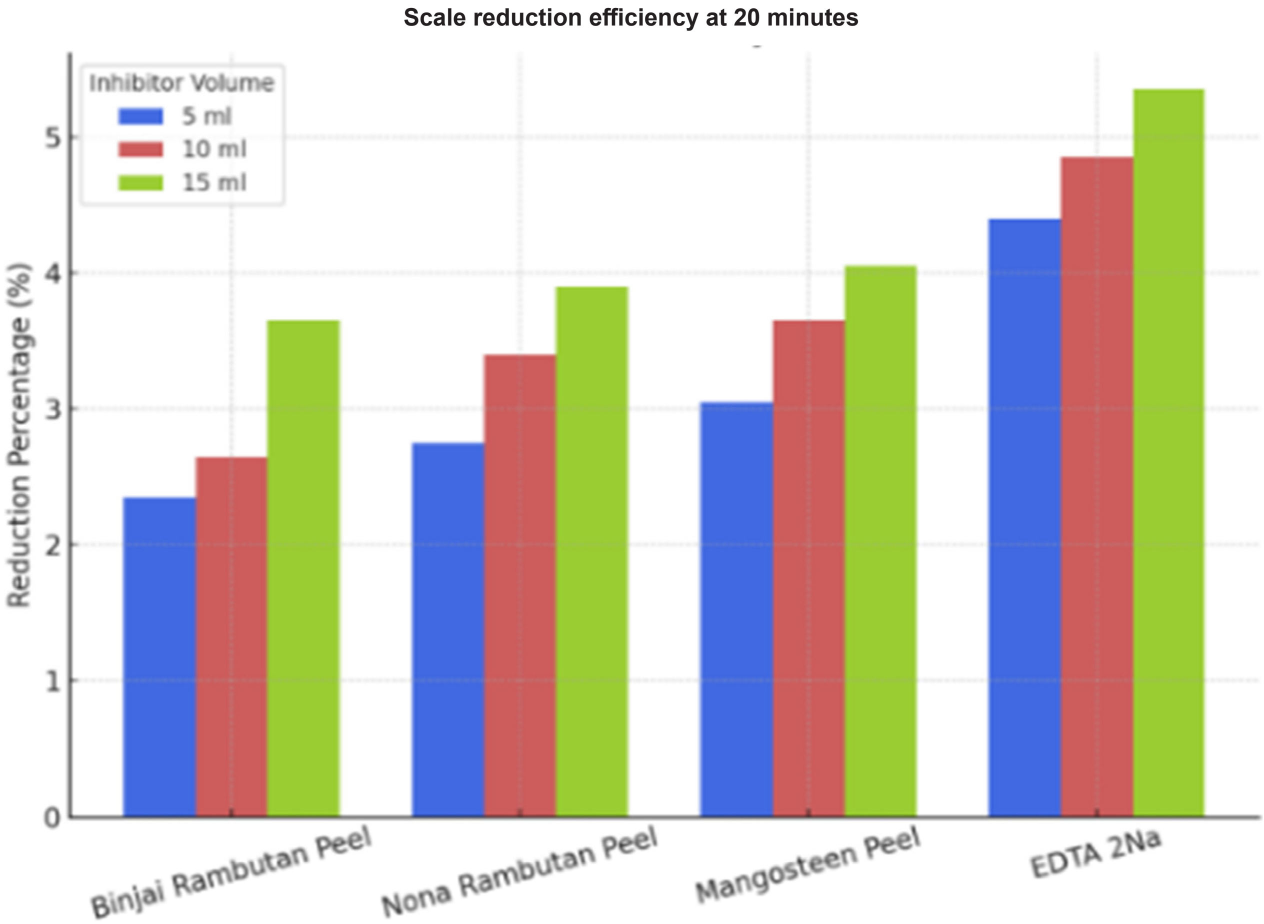

Figure 8. Effectiveness of scale Inhibitor at soaking time 20 minutes

Comparative study of scale inhibition efficiency: natural extract vs. Na_2EDTA at soaking time 60 minutes

The bar chart in Figure 9 has been used to compare the performance of four scale inhibitors tested against three dosage levels (5 mL, 10 mL, and 15 mL) over a set time immersion of 60 minutes. The results suggest that with growing inhibitor volume, there is a steady rise in scale-reduction effectiveness. This shows the high relevance of both dosage and contact time in minimizing mineral scale formation.

Among the natural inhibitors, mangosteen peel extract showed the highest inhibition performance, achieving a 6.6% reduction in scale mass at a 15 mL dosage. This efficiency surpassed rambutan nona (5.3%) and rambutan Binjai peel (4.35%) at the same concentration. The superior activity of mangosteen peel is attributed to the elevated content of polyphenolic compounds, particularly xanthones and flavonoids, which are recognized for the strong metal-chelating capabilities and surface adsorption affinity. Bioactive compounds disrupting mineral scale nucleation and growth have been studied to limit deposits.

All the compounds evaluated in this study showed varying levels of deposition reduction in the range from 0.0003 to 2.50%. Na_2EDTA, a prevalently used synthetic chelating agent, performed best overall, ridding deposition by 8.8% when given at 15 mL dosage. The best effectiveness of Na_2EDTA can be explained by the ability to form strong and stable coordination complexes with divalent cations Ca^{2+} and Mg^{2+}, as well as prevent the precipitation of typical mineral scale compositions, which include calcium carbonate and barium sulfate.

Previous studies have shown that the efficacy of chelation is dependent on the type of inhibitors, concentration levels, and solution pH. Based on the results pH values of rambutan Binjai peel extract, rambutan nona peel, mangosteen peel, and Na_2EDTA had pH values of 5.23, 5.14, 5.77, and 5.54, respectively. Although an adjusted higher pH

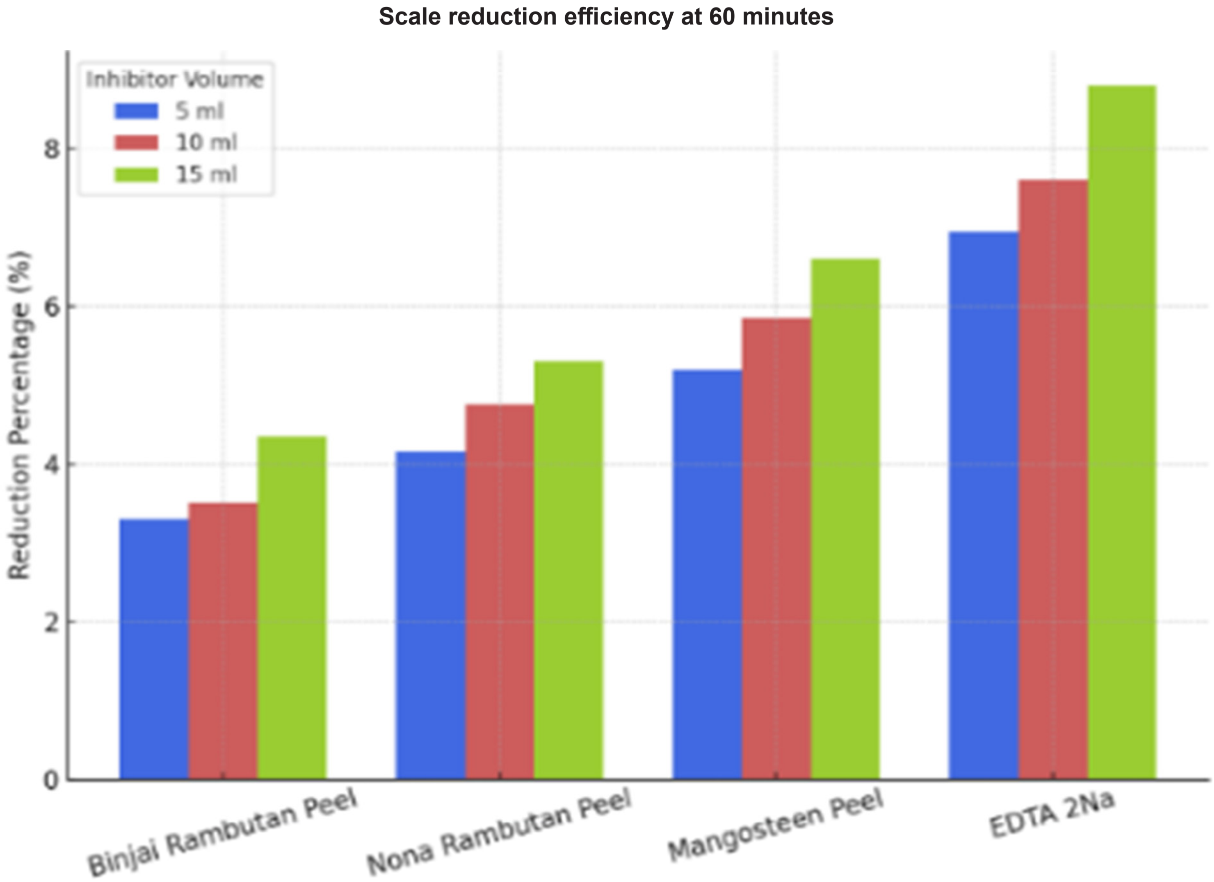

Figure 9. Effectiveness of scale Inhibitor at soaking time 60 minutes

was recorded in mangosteen extract, there was a tendency to promote complexation by decreasing the competition between H+ and metal cations, securing an active site in the functional groups. The lower pH effect in rambutan nona extract can prevent the complexing since there is a higher protonation of carboxyl and several phenolic functional groups as the pH decreases, thereby weakening the affinity towards binding with metals (Khormali & Petrakov 2016).

A commercial chelating agent, Na_2EDTA, showed scale prevention efficacy at pH 5.54, close to pH at scale precipitation (pH 6 in NaCl solutions). These results show that complexation based on EDTA is strong and can cluster metal ions under conditions where there are favorable conditions for dissolving calcium carbonate instead of precipitation. The data also support previous studies, showing the importance of molecular structure, dose, and environmental pH to scale-inhibition performance. More importantly, pH medium regulates the metal-ion concentration and magnitude of electrostatic products at the solid-liquid interface and controls the overall effectiveness of inhibition.

CONCLUSION

In conclusion, this study shows that natural and synthetic inhibitors can reduce scale formation rates when volumes and exposure times are deliberately manipulated. Among the natural agents tested, mangosteen peel extract shows the best performance, particularly when under high volume and long immersion times, with a 6.6% scale reduction at 15 mL retained over 60 mins. Despite the high efficacy of Na_2EDTA (8.8% reduction), this study shows that mangosteen peel extract is an excellent, environmentally friendly potential scale control candidate. The results also show the importance of maximizing the dosage and contact time in increasing the performance of inhibitors.

ACKNOWLEDGMENT

The authors are grateful to the Laboratory of the Petroleum Engineering Study Program at Universitas Islam Riau and PT Pertamina Hulu Rokan for the valuable support and contributions as well as the publication of this study.

GLOSSARY OF TERMS

Symbol	Definition	Unit
Na_2EDTA	Disodium Ethylenediaminet etraacetate	
HCl	Hydrogen Clorida	
HF	Hydrogen Fluorida	
$CaCO_3$	Calcium Carbonate	
$CaSO_42H_2O$	Calcium Sulfate Dihydrate	
$SrSO_4$	Strontium Sulfate	
$CaSO_4$	Calcium Sulfate	
$FeCO_3$	Ferrous Carbonate	
FeS	Iron Sulfide	
Fe_2O_3	Hematit	

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