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Original research article

Assessment of the Potential of Sodium Benzoate as Anti-Microbial and Anti-Corrosion Agent in Coolant

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ABSTRACT

Sodium benzoate, as both an antimicrobial agent and corrosion inhibitor, is ideally suited for application in engine coolant. This study evaluated the antimicrobial and anti-corrosion properties of sodium benzoate in an ethylene glycol-based organic engine coolant. Antimicrobial assays tested sodium benzoate against *Bacillus cereus, Pseudomonas aeruginosa*, and *Trichoderma viviens*. The corrosion inhibitory effect was assessed using the ASTM D1384 glassware corrosion test. It was found that 3% wt sodium benzoate strongly inhibited microbial growth, while a minimum dosage of 1% wt provided only mild antimicrobial performance. Interestingly, the presence of 50% ethylene glycol in the coolant outperformed sodium benzoate in antimicrobial effectiveness. Sodium benzoate also exhibited selective corrosion protection; at a dosage of 1% wt, it offered superior protection for aluminum but promoted corrosion of iron.

Keywords: Anti-bacterial; Anti-fungal; Corrosion inhibitor; Ethylene glycol coolant

1. Introduction

Sodium benzoate is widely known for its application as a preservative in various industries. It is a salt derivative of benzoic acid, a potent antimicrobial compound. Sodium benzoate is commonly used in pharmaceutical, cosmetics, food and beverages industries. In medical applications, it serves as a diuretic and therapeutic agent to treat sclerosis, liver diseases, and problems with the urea cycle [1]. In the automotive industry, sodium benzoate is employed

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as a corrosion inhibitor in coolant [2]. Ideally, sodium benzoate not only functions as a corrosion inhibitor but also as an antimicrobial agent, extending the service life of the coolant.

The coolant technology is increasingly shifting toward environmentally friendly, organic-based formulations, as opposed to conventional inorganic-based coolants. Organic coolants can be formulated with carboxylic based compounds, azole derivatives, sugars, plant extracts and some simpler form of protein related compounds [3]. These organic additives can serve as a carbon source, allowing bacteria and fungus to thrive within the coolant. The presence of organic compounds and oxygen in coolant provide ideal conditions for microbial growth. Additionally, the metabolism of dead cells can provide nutrients that further promote microbial proliferation in industrial coolant [4].

In the machining industry, bacteria and fungus found in metalworking fluid, also known as industrial coolant, are the primary concern, due to their potential to act as pathogens and spoilage agents. Studies on metalworking fluids have identified that bacterial growth in coolants is predominantly Gram-negative, including species such as *Escherichia coli, Salmonella typhi, Acinetobacter, Pseudomonas aeruginosa, Pseudomonas oleivorans*, and *Alcaligenes*. Gram-positive bacteria found include *Staphylococcus aureus, Streptococcus pneumoniae*, and *Bacillus*. Fungal contamination in coolants typically involves species such as *Aspergillus, Cladosporium, Fusarium, Penicillium*, and *Cephalosporium* [4, 5]. The growth of microorganisms in the metalworking fluid leads to the formation of the slimy biofilm, which is resistant to common disinfectants, facilitating clogging of the machining system [5].

Sodium benzoate in coolants provides both antimicrobial and corrosion inhibiting functions. It effectively inhibits corrosion of steel, iron, copper and aluminum [3, 6]. Additionally, sodium benzoate has demonstrated synergistic effect with silicates, offering high inhibition efficacy toward magnesium alloy [7].

Potassium sorbate has also shown potential as a corrosion inhibitor for metal alloys. It can inhibit the corrosion of biodegradable magnesium alloy at a dosage of 1.5%w/v [8]. Khlopyk et al. [9] reported its performance in inhibiting aluminum corrosion when mixed with guar gum. Other studies have consistently reported its effectiveness in inhibiting copper corrosion [10-13]. However, the stability of potassium sorbate in aqueous medium is comparatively weaker. Studies found that the concentration of potassium sorbate in preserved aqueous sample decreased to 65% of its initial concentration within 3 months at room temperature with reduced light exposure. For food preservation, its concentration dropped to less than 25% of the initial dosage after 40 days at 35°C. Moreover, the C=C double bond in potassium sorbate can react with carboxyl group in the sample, altering the chemical composition [14]. Thus, sodium benzoate is preferred over potassium sorbate for coolant formulations intended for long service life due to its superior stability and chemical compatibility. While sodium benzoate is widely used as an antimicrobial agent in the food and pharmaceutical industries, and as a corrosion inhibitor in engine coolants, systematic studies evaluating its dual functionality—for both metal protection and antibacterial performance within coolant systems—remains notably scarce. Hence, this paper reports the anti-microbial and anti-corrosion behavior of sodium ben-

zoate in ethylene glycol-based coolant. To the best of our knowledge, this is the first study to evaluate the potential of sodium benzoate as both an antimicrobial and anticorrosion agent in coolant formulations. This study addresses this critical gap by investigating the corrosion inhibition potential and functional performance of sodium benzoate in coolant systems. The findings offer valuable insights for optimizing coolant formulations, particularly in enhancing both metal protection and antibacterial effectiveness.

2. Materials and Methods

2.1 Coolant formulation, bacterial and fungal strains

Coolant samples containing ethylene glycol (EG) and water in a 1:1 ratio, supplemented with 1% and 3% wt sodium benzoate, were prepared for antibacterial and antifungal assays. Sodium benzoate in distilled water at 1% and 3% wt, respectively, was also prepared. The sodium benzoate-fortified coolant and sodium benzoate solution samples were filtered through a 0.45 μm membrane filter to remove microbial contamination. Gram-positive and Gram-negative bacteria of Bacillus cereus and *Pseudomonas aeruginosa*, respectively were chosen for evaluation. *Pseudomonas aeruginosa* used was ATCC strain, ATCC27853 and Bacillus cereus was isolated from a local soil sample. Bacillus cereus was identified via comparison of its 16S rRNA with that in GenBank database. The fungal species *Trichoderma virens* was tested. It was isolated from local soil and identified based on Internal Transcribed Spacer (ITS) sequence similarity through comparison with reference sequences in the GenBank database. For the anti-corrosion test, three coolant formulations were evaluated: a 50% ethylene glycol (EG) coolant, a 50% EG coolant supplemented with 0.5% (w/w) sodium benzoate, and a proprietary organic coolant dosed with sodium benzoate ranging from 0.3% to 1.0% wt.

2.2 Antibacterial assay

The anti-microbial activity of sodium benzoate was examined based on two approaches – the disc diffusion method and the broth dilution method.

For disc diffusion analysis, the bacteria were inoculated in nutrient broth and incubated at 37 °C in a shaking incubator (N-BIOTEK Brand, NB-205L model) for at least one day until the minimum turbidity of 0.5 McFarland was attained. The concentration of inoculum was determined using the UV-Vis spectrophotometer (Metertech Brand, SP-830 PLUS model) at the wavelength of 625 nm. Mueller Hinton agar was used as culture medium. The agar plates were prepared and streaked with sterile cotton swab dipped in standardized bacterial inoculum of 0.5 McFarland.

After the culture plates were prepared, filter paper discs of 3 mm diameter were placed onto the inoculated agar surface, positioned at a minimum distance of 24 mm between the disks and 10-15 mm from the edge of the plates. A 20 μL of sodium benzoate solution and sodium benzoate coolant at varying concentrations were pipetted onto the filter paper discs.

For positive control, the filter paper disc was pipetted with 20 μL of 1 mg/mL ampicillin. The plates were incubated in an inverted position at 37 °C (optimum temperature for bacteria growth). The diameter of inhibition zone was measured using a ruler after 24 hours. The size of the inhibition zone is an indication of the antimicrobial efficacy. The larger the inhibition zone is, the higher the antimicrobial ef-

ficiency.

For the broth dilution method, bacteria were inoculated in nutrient broth for 1 day. The concentration of the bacterial culture was then measured using the UV-Vis spectrophotometer, with absorbance at 625 nm recorded. An aliquot of the concentrated bacterial culture in nutrient broth was diluted in sterilized Mueller-Hinton broth (21 g/L) to achieve a culture solution (5 mL) with an absorbance between 0.08 and 0.12, corresponding to approximately 0.5 McFarland. The inoculated solution was then added with 1% and 3% wt of sodium benzoate solution, respectively. The solution was swirled to ensure homogenization and incubated at 37 °C in a shaking incubator. Each inoculated solution was prepared in 5 replicates. The samples were scanned using UV-Vis spectrophotometer at 625 nm on Day 0, 1, 3 and 6. The procedure was repeated on sodium benzoate-fortified coolant samples. The broth dilution method was adapted from Moghayedi et al. [15] with slight modifications.

2.3 Antifungal assay

The Mueller Hinton agar containing sodium benzoate (1% and 3% wt) in distilled water and 50% EG, respectively, was prepared. The agar with distilled water and 50% EG only were used as the blank. The culture of *Trichoderma viviens* was cut to approximately 6 mm in diameter from its culture plate and placed in the middle of tested agar plates. The fungal ring was observed on Day 1, 3, 5 and 7. A smaller diameter of fungal growth ring indicates stronger antifungal strength of the tested substrates. The study was performed in triplicates.

2.4 Anti-corrosion assay

The anti-corrosion properties were evaluated using the glassware corrosion test, following ASTM D1384. This method assesses the corrosion protection performance of engine coolants on six metals: copper, solder, bras, steel, cast iron, and aluminum. Briefly, a test solution containing a blank coolant, and a proprietary organic coolant, both with and without sodium benzoate, were mixed with corrosive water containing 100 ppm of sodium-based sulfate, chloride, and bicarbonate anions to yield a 33.33% coolant solution. The proprietary coolant, which consists of a mixture of mono- and di-carboxylate, azole and triazine derivatives, does not contain sodium benzoate. Metal plates made from the aforementioned metals were prepared according to standard specifications. Each plate was cut into 5 × 2 inches with a 3 mm thickness. The plates were arranged in galvanic coupling to promote corrosion (as shown in Fig. 1) and suspended in 750 mL of the coolant solution within a glass vessel. The plates, submerged in the coolant containing corrosive water, were then heated and maintained at 88 ± 2 °C for 14 days, with aeration supplied at a rate of 100 mL/min. To minimize temperature fluctuations, the glass vessel was placed in a sand bath to reduce heat loss to the surroundings. After the test period, the metal plates were removed, cleaned and dried according to ASTM requirements. The weight loss of each plate (measured in milligram (mg)) was recorded, where lower weight loss indicates better corrosion protection.

2.5 Statistical analysis

Analysis of Variance (ANOVA) was used to determine significant differences in the antimicrobial properties among different sample groups at a 95% confidence

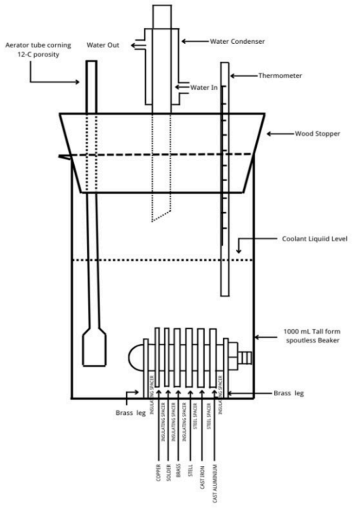

Fig. 1. Experimental setup for glassware corrosion testing of coolant formulations. The apparatus consists of a 1000 mL tall-form beaker containing metal coupons (brass, copper, cast iron, cast aluminum, solder and steel) mounted on a brass leg. Coolant is aerated with a water condenser and a thermometer inserted through a wood stopper to maintain the temperature.

level. Tukey's test was then applied for multiple comparisons. Statistical analysis was performed using Microsoft Excel and Matlab R2024a.

3. Results and Discussion

3.1 Anti-microbial activity

Fig. 2 shows the microbial inhibitory actions of sodium benzoate-containing coolant and sodium benzoate solutions, ranging from 0.3% to 3% wt, against *Pseudomonas aeruginosa* using the disc diffusion method. Interestingly, none of the plates displayed any inhibition zone after 24 hours, whereas the positive control with ampicillin showed a clear inhibition zone of 34 mm. This observation implies that sodium benzoate was ineffective against *Pseudomonas aeruginosa* both in the coolant and as a standalone solution. There are conflicting findings in the literature on the antimicrobial properties of sodium benzoate. Bubonja-Šonje et al. [16] noted that the absence of an inhibition zone might due to the slower diffusion of the test agent in aqueous agar. Some studies have also revealed that the antimicrobial efficacy of sodium benzoate is pH dependent. Chen and Zhong [17] reported that 1% wt sodium benzoate exhibited no antimicrobial effect at pH 7.0, but lowering the pH value increased its efficacy, with the highest activity achieved at pH 2.0 using only 0.1% of sodium benzoate. Likewise, Maherani et al. [18] tested sodium benzoate using the agar disc diffusion method and concluded that solutions with a pH 2.5-3.0 exhibited antimicrobial activity. This is because, under acidic condition, benzoate ion converts to benzoic acid which demonstrates antibacterial properties. On the other hand, pharmaceutical studies have shown that liquid drug samples containing 20% sodium benzoate at pH 8.14 exhibited antimicrobial effects [19]. This contrasts with the report by Chen and Zhong [17], where no inhibition was recorded with a 1% wt sodium benzoate solution at pH 7.0, likely due to the relatively low dosage. The observation suggests that the antimicrobial function of sodium benzoate in alkaline conditions is dosage dependent, which defines the equilibrium state of sodium benzoate in solution. In acidic pH, more benzoate ions convert to benzoic acid, increasing the ratio of benzoic acid to benzoate ion which enhances the antibacterial properties of sodium benzoate. Conversely, in alkaline pH, the ratio of benzoic acid to benzoate ions is lower than in acidic conditions. Therefore, the concentration of benzoic acid available in solution can only increase when the dosage of sodium benzoate is increased.

The coolant is prepared with EG

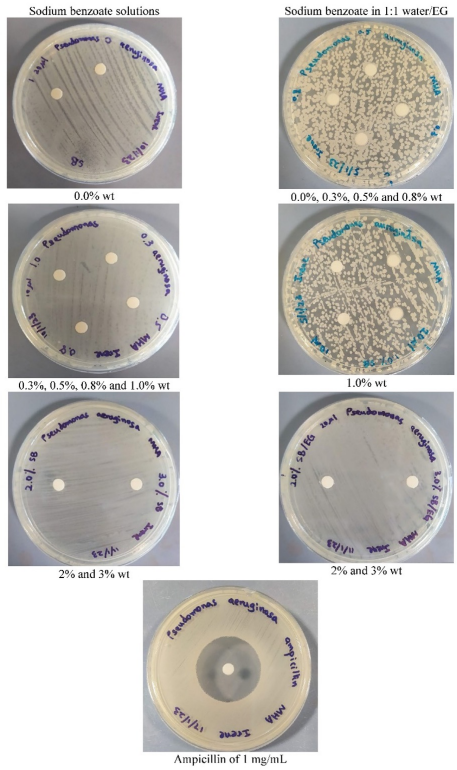

Fig. 2. Anti-bacterial activity of sodium benzoate solution and sodium benzoate coolant towards *Pseudomonas aeruginosa* after 1 day, based on the disc diffusion method.

as the matrix. Moghayedi et al. [15] reported that EG is a bactericidal agent, capable of completely inhibiting bacteria growth within 4 hours at 25% concentrations. However, in the present study, no inhibitory effect was observed on the growth of *Pseudomonas aeruginosa* with 50% EG. The variation in observations is likely due to the differences in methods; Moghayedi et al. [15] employed the broth turbidity assay, whereas the present study used the disc diffusion method. When an aliquot of sodium benzoate solution containing 50% EG was added to the disc on agar, the solution diffused into the agar medium, diluting the concentration of EG to levels where its antimicrobial properties were negligible. It is therefore concluded that the disc diffusion assay is not effective in determining the antimicrobial properties of sodium benzoate. Additionally, the disc diffusion method cannot distinguish between the bactericidal and bacteriostatic effects of the antimicrobial agents tested [16].

The antimicrobial activity of sodium benzoate was repeated using the broth dilution method. Fig. 3 illustrates the absorbance of inoculated solutions containing sodium benzoate in distilled water over time for both *Pseudomonas aeruginosa* and *Bacillus cereus*. As observed, *Pseudomonas aeruginosa* underwent exponential growth in the control broth on Day 3, while Bacillus cereus reached exponential growth on Day 1. Typically, bacterial growth progresses through four phases:

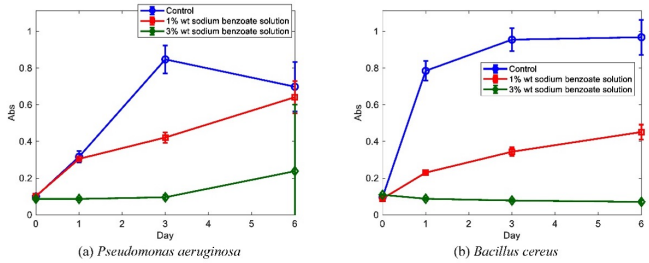

Fig. 3. Anti-bacterial activity of sodium benzoate solutions against (a) *Pseudomonas aeruginosa* and (b) *Bacillus cereus*, based on the broth dilution method.

lag, exponential, stationary, and death [20]. During the lag phase, there is a delay in bacterial growth as the bacteria adapt to the new environment [21]. In the presence of a 1% wt sodium benzoate solution, both *Pseudomonas aeruginosa* and *Bacillus cereus* showed gradual growth over 6 days, with exponential growth not clearly defined. This gradual growth is likely due to the antimicrobial effect of sodium benzoate, which creates unfavorable conditions for bacterial proliferation. Conversely, at a 3% wt sodium benzoate solution, no apparent increase in bacterial inoculum was recorded over the 6 days, indicating effective inhibition of bacterial growth. Statistically, there was a significant difference in the bacterial concentration of *Pseudomonas aeruginosa* from Day 0 to Day 6 ($p < 0.05$) in both the control and 1% wt sodium benzoate solutions. In contrast, no significant difference in bacterial growth was observed in the 3% wt sodium benzoate solution over the 6-day period ($p > 0.05$).

Bacillus cereus enters the stationary growth phase from Day 3 to Day 6 in the control sample, with no significant increase in bacterial density ($p > 0.05$) (Fig. 3). During the stationary phase, bacterial growth and cell death are in equilibrium. Although bacteria can still proliferate, dead cells that lyse provide a carbon source during nutrient deficiency, leading to the accumulation of waste materials and toxic compounds, which create unfavourable pH conditions for further bacterial growth [20]. In the presence of a 1% wt sodium benzoate solution, the growth rate of Bacillus cereus is reduced with a significant difference in bacterial density over 6 days ($p < 0.05$). Similar to *Pseudomonas aeruginosa, Bacillus cereus* treated with a 3% wt sodium benzoate solution exhibits no net growth ($p > 0.05$) indicating a reduction and a tendency for bacterial density to remain stable from Day 3 onward. Thus, 3% wt sodium benzoate solutions are more effective than 1% wt solutions against both *Pseudomonas aeruginosa* and *Bacillus cereus*.

The growth behavior of *Pseudomonas aeruginosa* and *Bacillus cereus* in pure ethylene glycol is depicted in Fig. 4. With the addition of EG, the bacterial growth patterns of both *Pseudomonas aeruginosa* and *Bacillus cereus* were altered, clearly different from sodium benzoate solutions. Statistically, the bacterial growth is generally stable and there is no net growth in bacterial density for either *Pseudomonas aeruginosa* or *Bacillus cereus* over 6 days ($p > 0.05$). These results corroborate the findings of

Moghayedi et al. [15] and demonstrated the bactericidal effect of EG by totally inhibiting bacteria growth. In the control sample EG: Mueller-Hinton broth (1:1) without sodium benzoate, both *Pseudomonas aeruginosa* and *Bacillus cereus* demonstrated reduction instead of bacterial growth over 6 days (Fig. 4). The bacterial density in the control for *Bacillus cereus* stabilized after Day 1 ($p > 0.05$), whereas those of *Pseudomonas aeruginosa* reduced on Day 1 but continued to increase over 6 days ($p < 0.05$). *Pseudomonas aeruginosa* is an aerobic bacterium; it can consume EG through oxidation and oxidase reaction [22] as well as metabolize ethanol and acetate, which are byproducts of the aerobic degradation process, with the aid of the ethanol oxidizing enzyme [23]. Likewise, the bacterial densities of both *Pseudomonas aeruginosa* and *Bacillus cereus* were reduced with 1% and 3% wt sodium benzoate coolants over 6 days. The number of dead cells exceeds the number of viable cells in sodium benzoate coolant. However, the concentration of sodium benzoate has little impact on the anti-bacterial performance of coolant due to the strong bactericidal effect of EG, which renders the anti-microbial strength of sodium benzoate in coolant insignificant. The anti-microbial properties of sodium benzoate coolant/solutions and pure EG are compared, as shown in Fig. 5. The 3% wt sodium benzoate solution shows greater anti-microbial activity against *Pseudomonas aeruginosa* and *Bacillus cereus* without noticeable increase in bacteria density over 6 days, as compared to the 1% sodium benzoate solution. In addition, Bacillus cereus demonstrates more sensitive reactions towards 1% wt sodium benzoate solution than *Pseudomonas aeruginosa*. Gram-negative bacteria have a more resistant cell membrane structure than Gram-positive bacteria, with three layers of outer membrane, peptidoglycan cell wall, and inner membrane [24].

Pure EG exhibits a strong bactericidal effect on both bacterial species, leading to retarded cell growth over 6 days, as evidenced by the low absorbance values. The microbial inhibition performance of 1% and 3% wt sodium benzoate coolants was comparable to that of pure EG, suggesting that the antimicrobial effect of EG surpasses that of sodium benzoate. In sodium benzoate coolants with 50% EG as the matrix, microbial growth inhibition was more effective than in sodium benzoate solutions alone, rendering the antimicrobial contribution of sodium benzoate insignificant. The absorbance of a 3% wt sodium benzoate solution without EG was slightly higher than that of the EG-based coolant, indicating that the latter demonstrates better inhibitory efficiency. In 1% sodium benzoate, the microbes showed signs of stress but continued to proliferate. This result is consistent with the findings of Chen and Zhong [17], who reported that 1% sodium benzoate at pH 7.0 does not inhibit microbial growth.

3.2 Antifungal activity

The growth of Trichoderma viviens on MHA added with 1% and 3% wt sodium benzoate is shown in Figs. 6-7, respectively. The growth of Trichoderma viviens was noticeably slower in 1% wt sodium benzoate dosage compared to the blank MHA. This confirms the fungistatic properties of sodium benzoate in suppressing fungal growth, aligning with the findings of Yadav et al. [25]. At a concentration of 3% wt, no fungal growth was visually detectable. Similarly, with 50% EG, the growth of Trichoderma virens was completely inhibited (Fig. 8). This study concludes that

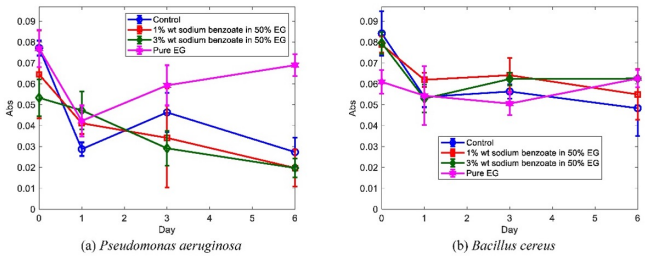

Fig. 4. Anti-microbial effect of sodium benzoate coolant, addition with EG, towards (a) *Pseudomonas aeruginosa* and (b) *Bacillus cereus*.

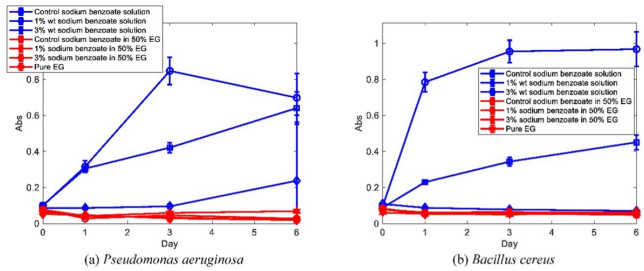

Fig. 5. Anti-microbial properties of sodium benzoate solutions/coolant and pure ethylene glycol on (a) *Pseudomonas aeruginosa* and (b) *Bacillus cereus*.

3% wt sodium benzoate solution possesses stronger anti-fungal properties than those of 1%. In the presence of EG, particularly in new and unused coolant, fungal growth is effectively eliminated, thereby ensuring the coolant's shelf life.

3.3 Anti-corrosion activity

Table 1 showcases the metal loss (in mg) of copper, solder, brass, steel, cast iron, and aluminum during the glassware corrosion test. It is observed that the presence of 0.5% wt sodium benzoate as a single inhibitor in the coolant effectively protected all metals except iron. Interestingly, sodium benzoate significantly accelerated iron loss, with 392 mg of iron loss compared to 92 mg in the blank 50% EG solution. Afshari and Dehghanian [6] revealed that a protective film was formed on iron surfaces at a concentration of 1.4% wt when applied individually. This indicates the dosage-dependent behavior of benzoate in anti-corrosion performance. However, their findings were based on salt water testing at room temperature, which differs considerably from the more exhaustive conditions of coolant corrosion tests. Increasing the dosage of benzoate may offer protection for iron but promote corrosion for other metals, such as aluminum. Asadikiya et al. [2] reported that sodium benzoate could exhibit corrosive properties toward aluminum by forming an unstable film on its surface. At a 1% wt dosage, sodium benzoate increased the corrosion rate of aluminum. Raspini [26] reported that benzoate forms an insoluble corrosion by-product on the surface of aluminum. The accumulation

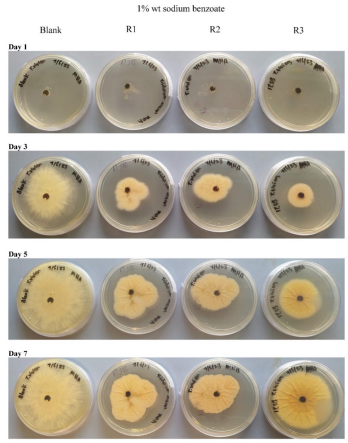

Fig. 6. Growth behavior of fungus *Trichoderma viviens* on blank Mueller-Hinton Agar (MHA) and 1% wt sodium benzoate solution in agar over 7-day.

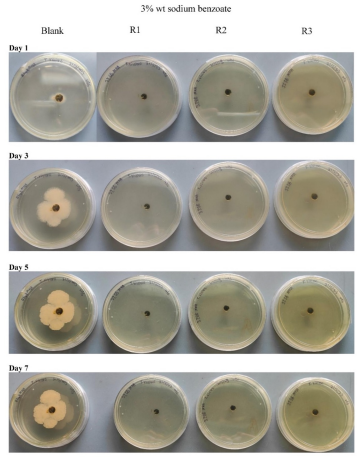

Fig. 7. Anti-fungal effect of 3% wt sodium benzoate solution on *Trichoderma viviens* over a 7-day period.

of this by-product on aluminum increased as the benzoate concentration rose from 0.5 to 3% wt, further confirming the corrosiveness of benzoate at higher dosages. This finding also highlights the selective behavior of sodium benzoate in metal protection. When used as a standalone inhibitor in coolant, sodium benzoate protects aluminum while corroding iron at dosages below 1% wt. However, at concentrations of 1% wt and above, its effects on both metals are likely reversed.

The addition of sodium benzoate to a proprietary coolant effectively protects steel, copper, brass, and solder. This level of protection is comparable to that of the coolant itself (blank), suggesting that sodium benzoate exhibits minimal anti-corrosion effects on these metals. On the other hand, aluminum experienced increasing damage as the concentration of sodium benzoate rose from 0.3% to 0.6%. How-

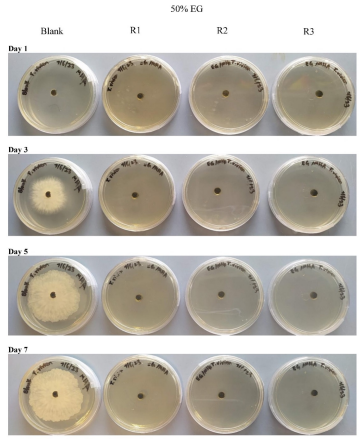

Fig. 8. Growth behavior of *Trichoderma viviens* on blank Mueller-Hinton Agar (MHA) and 50% EG MHA over 7 days.

Table 1. Average metal loss of six elements in coolant supplemented with varying concentrations of sodium benzoate (n = 2). Values in brackets indicate percentage mass loss. CBlank refers to the proprietary coolant without sodium benzoate in the formulation.

	Mass loss (mg)						
Metal	50% EG	0.5% sodium benzoate/EG	Proprietary Coolant (CBlank)	CBlank + 0.3% wt sodium benzoate	CBlank + 0.5% wt sodium benzoate	CBlank + 0.6% wt sodium benzoate	CBlank + 1.0% wt s odium benzoate
Aluminum	21±2 (0.3)	13±1 (0.18)	41±2 (0.61)	65±1 (0.99)	88±2 (1.26)	93±3 (1.32)	2±1 (0.03)
Iron	92±4 (0.38)	392±18 (1.52)	4±1 (0.02)	37±4 (0.14)	44±3 (0.17)	42±1 (0.18)	50±3 (0.19)
Steel	29±3 (0.21)	22±1 (0.16)	7±1 (0.05)	7±1 (0.05)	1±0 (0.01)	4±1 (0.03)	2±1 (0.01)
Brass	16±1 (0.05)	4±1 (0.01)	4±1 (0.01)	6±1 (0.02)	0 (0.00)	2±1 (0.01)	5±1 (0.02)
Solder	86±7 (0.39)	55±4 (0.25)	2±1 (0.01)	8±1 (0.03)	5±1 (0.02)	6±1 (0.03)	4±1 (0.02)
Copper	19±1 (0.07)	6±1 (0.02)	1±1 (0.00)	5±1 (0.02)	1±0 (0.00)	1±0 (0.00)	1±0 (0.00)

ever, a further increase in dosage to 1% sharply reduced aluminum loss to 2 mg. This observation contradicts the findings of Rosliza et al. [27], who claimed that sodium benzoate is effective in protecting aluminum. Their study revealed that 0.1% wt sodium benzoate provided protection for aluminum at room temperature and in the presence of sodium chloride.

Essentially, anti-corrosion inhibitors function by forming a protective layer on the metal surface. In the proprietary coolant, the co-occurrence of mono- and dicarboxylate inhibitors, which are mostly aliphatic in nature [28-30], competes with benzoate ions for active sites on the metal surface. The competition between sodium benzoate and carboxylate inhibitors disrupts the formation of a well-packed, protective inhibitor layer on the metal surface. Additionally, sodium benzoate has been found to form an unstable and non-protective film on the aluminum surface [2]. As a result, more aluminum is exposed to the corrosive environment, leading to increased corrosion. This explains why aluminum loss was higher in the coolant containing 0.3–0.6% wt sodium benzoate com-

pared to the coolant without sodium benzoate. When sodium benzoate concentration reaches 1% wt, the corrosion behavior differs from when it is used as a standalone inhibitor. This suggests that in the proprietary coolant (which contains other inhibitors), sodium benzoate might interact differently at higher concentrations, possibly stabilizing its effect or modifying how it interacts with the metal surface.

Similarly, iron undergoes severe corrosion in the presence of sodium benzoate in the coolant. Iron loss increased significantly from 4 mg to 37 mg when 0.3% wt sodium benzoate was added, compared to the blank. Unlike aluminum, where higher sodium benzoate concentrations reduced corrosion, increasing the dosage to 1% wt did not mitigate iron loss. Instead, iron loss further increased from 37 mg to 50 mg. These observations indicate that sodium benzoate in coolant does not provide protection for iron, contradicting the findings of Afshari and Dehghanian [6], who reported that sodium benzoate protects iron at 1.44% due to differences in test conditions. Maltseva et al. [31] reported that benzoate ions can bind with iron, forming a soluble complex that leads to iron dissolution and corrosion. In the blank coolant (without sodium benzoate), iron loss is very low (only 4 mg). When benzoate ions are introduced, they disturb the compact arrangement of the protective carboxylate layer. This exposes more of the iron surface to the coolant, making it vulnerable to corrosion.

Benzoate has a dissolving effect on iron, and its presence competes with other inhibitors, disrupting the arrangement of the protective layer. As its concentration increases, corrosion worsens. The findings of this study reveal that sodium benzoate provides protection for aluminum at a 1% wt and exhibits synergistic interactions with other inhibitors. However, it does not protect iron and may even weaken the protection provided by other inhibitors.

4. Conclusion

This study evaluated the application of sodium benzoate as both an antimicrobial agent and a corrosion inhibitor in engine coolant. The findings provide novel insights into its antimicrobial and anticorrosion properties. In this study, we identified the lack of sensitivity of the disc diffusion technique for the quantitative evaluation of antimicrobial properties. In contrast, UV-Vis spectrophotometry for turbidity measurement offers enhanced sensitivity in determining microbial growth. The antimicrobial tests concluded that a 3% wt dosage of sodium benzoate in coolant strongly inhibits microbial growth, while a minimum dosage of 1% wt exhibits a mild antimicrobial effect. Additionally, the presence of 50% ethylene glycol (EG) in the coolant ensures complete inhibition of bacterial and fungal growth, thereby prolonging the shelf life of the engine coolant. Regarding its anti-corrosion behavior, sodium benzoate exhibits selective and dosage-dependent properties as a corrosion inhibitor. When applied as a standalone inhibitor at 0.5% wt, it corrodes iron while protecting aluminum. Increasing the dosage can reverse its protective behavior between these two metals. However, in the proprietary coolant, which contains a mixture of inhibitors, sodium benzoate at concentrations below 1% wt corrodes both aluminum and iron. At 1% wt, sodium benzoate provides excellent protection for aluminum but continues to exhibit corrosive effects on iron. These findings suggest that an additional iron corrosion inhibitor, chemically compatible with

sodium benzoate, is required when formulating coolants. Overall, sodium benzoate at 1% wt is capable of delivering both antimicrobial and anticorrosive properties.

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