Malaysian Journal of Chemical Engineering & Technology

Journal Homepage: http://myjms.mohe.gov.my/index.php/mjcet

e-ISSN: 2682-8588

Safety and health assessment of corrosion inhibitors using an index-based methodology

[a] Siti Rafidah Ab Rashid*, [a] Mohamad Khairul Anwar Mohamad Rasidin, [a] Nor Roslina Rosli

[a]School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA, Selangor, Malaysia

*Corresponding email: sitirafidah660@uitm.edu.my

Abstract

Corrosion inhibitors are extensively used for the protection of materials against corrosion due to their simplicity in application. Despite the advantage, many corrosion inhibitors contain organic compounds that pose toxicity concerns. This study focused on the assessment of the safety and health risks associated with the usage of various types of corrosion inhibitors using an index-based methodology. The analysis focused on the toxicity of corrosion inhibitors and their influences on the environment. The outcome presents a set of criteria for choosing commonly used corrosion inhibitors. This case study evaluated five different types of corrosion inhibitors, namely sodium molybdate, sodium bisulfite, potassium silicate, phosphate ester, and dicyclohexylamine nitrite. Based on the results of the safety sub-index, sodium molybdate and potassium silicate were the safest corrosion inhibitors based on their scores of zero for both flammability and chemical reactivity. However, the results from the health sub-index revealed that sodium molybdate was the only safest corrosion inhibitor. It can be concluded that the systematic nature of the index-based assessment could provide a useful method of analysing a wide variety of chemical substances from industrial applications to household items.

Article Info

https://doi.org/10.24191/mjcet.v6i1.19549

Article history:

Received date: 7 September 2022
Accepted date: 4 April 2023
Published date: 30 April 2023

Keywords:

Corrosion inhibitor
Safety and health index
Mixed Inhibitor
Health, safety and environment (HSE)

1.0 Introduction

Corrosion is a natural process that happens when a substance (usually a metal) degrades due to contact with its surroundings. Corrosion not only affects aesthetically but deteriorates material performance and safety which can destroy anything from automobiles to household appliances, drinking water systems, pipelines, bridges, and public infrastructure (Ranjith et al., 2016). In many organisations, effective utilisation of building materials while maintaining a budget is critical. Corrosion influences every area of the economy, and the cost of corrosion is estimated to be 4% of GDP. These values include direct losses such as the cost of replacing corroded materials and equipment, as well as indirect losses such as the cost of repair and lost productivity, and the cost of corrosion protection and prevention (Hou et al., 2017; Koch, 2017).

Corrosion prevention can be achieved in so many ways. Despite advancements in corrosion-resistant materials, chemical inhibitors are still the most practical and cost-effective method of corrosion prevention especially in the oil and gas industry (Haldhar et al., 2021; Zehra et al., 2022).

Corrosion inhibitors come in various forms based on their mechanism, class of chemicals, and application (Topçu & Uzunömeroğlu, 2020). Anodic inhibitors, cathodic inhibitors, organic and inorganic corrosion inhibitors, volatile corrosion inhibitors, and mixed inhibitors are the types of corrosion inhibitors available in the market. Anodic inhibitors are substances that form a protective oxide layer on a metal's surface, preventing corrosion. Cathodic inhibitors slow down or precipitate cathodic areas to increase surface impedance at the cathode. Organic inhibitors, often known as ‘film-forming’ inhibitors, protect the metal by covering it with a hydrophobic layer. VCIs (volatile corrosion inhibitors) are chemical inhibitors that progressively volatilise and release chemicals within sealed airspace, actively preventing metal surface corrosion. Mixed inhibitors block both the anodic and cathodic processes involved in the corrosion process (Ma et al., 2021).

Despite its advantages, typical corrosion inhibitors are toxic organic compounds that are hazardous to humans and the environment. The challenge in designing a corrosion inhibitor is to achieve the requirements without jeopardising the corrosion inhibitor's safety and health impacts. There are two safety concerns to consider when utilising corrosion inhibitors in the oil and gas business. The first one is the impact of chemical reagents in corrosion inhibitors on human health and the environment (Tang, 2019; Yan et al., 2022). The second concern is the proper handling of corrosion inhibitors by workers systematically (Aslam et al., 2021; Prasad et al., 2020).

Limited studies have been done to thoroughly evaluate the chemical compounds in corrosion inhibitors in terms of their health and safety aspects (Andersen, 2001; Raja et al., 2016). The bulk of previous research focused on safety issues, with flammability and toxicity being chosen as goal features, primarily during the formation of formed goods (Tamalmani & Husin, 2020). This study strives to fill this gap to assess the safety aspects of using various types of corrosion inhibitors and systematically classifying corrosion inhibitors available in the market based on their safety.

1.1 Chemical compound risk assessment approaches

There are several published safety and health assessment approaches for chemical process design and a few acknowledged safety and health evaluation processes for corrosion inhibitors. The Prototype Index of Inherent Safety (PIIS), Inherent Safety Index (ISI), and the i-Safe Index (Zainal Abidin et al., 2018; Zhu et al., 2022) were among the first index-based approaches to evaluate risks and select safer process alternatives. These methods are employed in the early phases of process design when only basic information such as the chemicals and conditions of the process is available. Safety qualities such as flammability, explosiveness, reactivity, and toxicity are considered while evaluating the inherent safety of a chemical process route. In addition, the Process Route Healthiness Index (PRHI) and the Inherent Occupational Health Index are two approaches for assessing inherent occupational health throughout research and development (R&D) (Warnasooriya & Gunasekera, 2017).

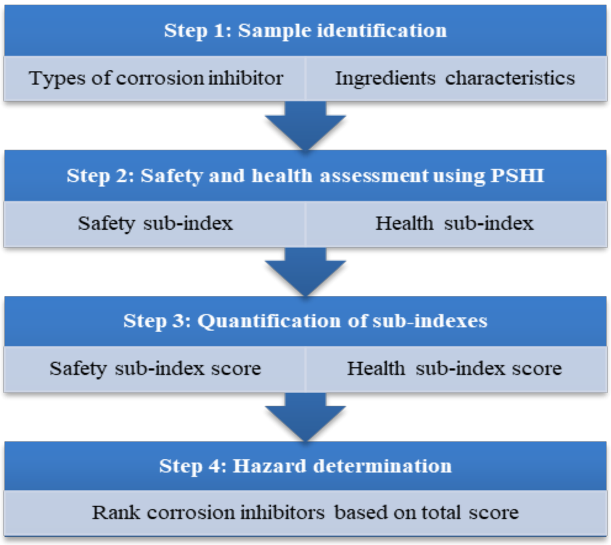

Fig. 1: Flowchart of the index-based safety and health assessment of corrosion inhibitors

Some of the health aspects assessed include the exposure limit, acute and chronic effects, inhalation, and skin contact. The same inherent safety and occupational health evaluation methodologies that were employed in the early phases of process design may be used in the early stages of formulated product design (Hassim & Hurme, 2010).

2.0 Methodology

In this case study, the Product Safety and Health Index (PSHI) method was applied. The scope of this work is confined to the chemical reactivity and flammability for the safety index, while covering a portion of the exposure through eye contact, inhalation, and skin contact for the health sub-index. To exemplify the suggested index approach, a case study on five corrosion inhibitors is presented in this work.

2.1 Product safety and health index (PSHI)

The PSHI method was originally applied for the safety and health assessment of paint formulations (Raslan et al., 2020). Since PSHI offers an estimate of the possible safety and health consequences of formulations that are comprised of chemical substances, it is intended that the application be applied here for corrosion inhibitors. Fig. 1 shows the four steps in assessing the safety and health of selected corrosion inhibitors. The first step was to identify the types of corrosion inhibitors in this case study. The five selected corrosion inhibitors were sodium molybdate, sodium bisulfite, potassium silicate, phosphate ester, and dicyclohexylamine nitrite (DICHAN). These selected inhibitors represent different types of corrosion inhibition mechanisms such as anodic corrosion inhibitors, cathodic corrosion inhibitors, organic and inorganic corrosion inhibitors, mixed corrosion inhibitors, and volatile corrosion inhibitors as tabulated in Table 1 (Alink et al., 1999; Tristijanto et al., 2020).

To demonstrate the score acquired by the components in the formulation, safety and health sub-indexes based on hazard statement data were used as examples. Scores were given based on a thorough assessment of the chemical compounds' Safety Data Sheet (SDS). The score will disclose the number of possible hazards from each chemical constituent used in product development.

The output of this assessment is the total score of both the safety and health index assessment for the corrosion inhibitors. The total score or index will conclude the exposure pathway for each corrosion inhibitor that is the most dangerous. A high score indicates a highly unsafe or unhealthy corrosion inhibitor and vice versa.

2.2 Index-based method

An index-based methodology is simply a set of instructions or a scope of study that has been chosen and recorded by the person doing the research. In assessing the level of safety, the toxicity information of each component in commercial corrosion inhibitors was assessed. The combination of both safety and health indices was employed to determine which corrosion inhibitor is the safest to use (Askari et al., 2021).

Table 1: List of selected corrosion inhibitor

Corrosion inhibitor	Type	Characteristics / Mechanism
Sodium molybdate Na_2MoO_4	Anodic inhibitor	Adsorption of Mo (VI) ions on the steel surface to form a film layer. Protecting the steel surface.
Sodium bisulfite $NaHSO_3$	Cathodic inhibitor	An oxygen scavenger that removes dissolved oxygen.
Phosphate esters	Anodic inhibitor, organic and inorganic inhibitors	Used as coatings and flame retardant. It is poorly soluble in water and adsorbs strongly to soils.
Dicyclohexylamine nitrite (DICHAN), $C_{12}H_{24}N_2O_2$	Volatile inhibitor	A light-coloured crystalline solid that is insoluble in water and denser than water. DICHAN vapour condenses on a metallic surface to make it less susceptible to corrosion.
Potassium silicate, K_2SiO_3	Mixed inhibitors	Commonly used as fertilizers. Soluble silicates function as absorption-type corrosion inhibitors.

2.3 Safety index

Corrosion inhibitors may be exposed to hazards during the application and storage of a chemical product. Accidental chemical discharge, leakage, and spillage from the container pose safety issues, culminating in fire and explosion (Baalisampang et al., 2018; Tuma, 2020). Safety sub-indices such as dust explosiveness, flammability, toxicity, and chemical reactivity are crucial elements that must be analysed (Gao et al., 2021; Zainal Abidin et al., 2018). In this study, the safety sub-indexes were grouped into 'Flammability' and 'Chemical Reactivity'. The analysis of a substance's flammability level was based on information on its flash point, autoignition temperature, and explosion limits. While for reactiveness, investigation was made through literature.

2.4 Health index

A chemical element in a product may enter the human body during delivery, storage, or any unintended incident. This can happen through four primary methods: eye contact, inhalation, ingestion, and skin contact (Md et al., 2019). The health sub-indices that were measured in this study were based on the exposure pathway to emphasise the source of the chemical components' consequences. The health sub-indexes measured in this work are shown in Table 2. The sub-indices are based on the current Inherent Occupational Health Index (IOHI) (Ying So et al., 2021). As an example, a consumer may be exposed to a harmful substance through eye contact if they do not wash their hands after applying a prepared product. If a corrosion inhibitor's chemical component encounters

Table 2: Health sub-indexes for corrosion inhibitors case study

Corrosion inhibitors	Safety issues	
	Flammability Score	Chemical reactivity Score
Sodium molybdate	0	0
Sodium bisulfite	0	2
Phosphate ester	2	3
Dicyclohexylamine nitrite	3	1
Potassium silicate	0	0

the eyes, it may linger in the eye and cause discomfort, illness or eye defect depending on the degree and length of exposure.

The Global Harmonized System (GHS) hazard statements, issued by the United Nations, was applied to assess the risk of eye contact, dermal contact and ingestion/inhalation to the worker. (Vorobyova et al., 2018; Winder et al., 2005; Yazid et al., 2020).

3.0 Results and discussion

3.1 Result and Discussion for Safety Sub-Index

The acquired score disclosed the amount of possible flammability and chemical reactivity of each corrosion inhibitor. Scoring of the safety sub-index was based on the following guidelines:

- Min = 0 (0%)
- Low = 1 (25%)
- Moderate = 2 (50%)
- High = 3 (75%)
- Extreme = 4 (100%)

The findings of the analysis of five case studies for the safety index were collated as shown in Table 3.

Sodium molybdate was given a score of 0 for both flammability and reactivity based on its MSDS which states its non-flammability and unreactive nature (Diamantino et al., 2000; Vukasovich & Robitaille, 1977).

Sodium bisulfite is a noncombustible substance with no available data on its autoignition temperature and explosion limits so, therefore, was given a score of 0 for its flammability (Nair & Elmore, 2003). Its estimated NFPA rating for instability is 2 so therefore the same score was given for its chemical reactivity.

Esters, on the other hand, are mostly flammable or highly flammable and reactive in nature. Phosphate esters are susceptible to the formation of toxic and flammable phosphine gas in the presence of strong reducing agents such as hydrides. Partial oxidation by oxidizing agents may result in the release of toxic phosphorus oxides (Cao et al., 2000; Cox & Ramsay, 1964). Phosphate ester was therefore given a score of 2 and 3 for its flammability and reactivity, respectively. DICHAN is a flammable solid that burns and propagates flame easily, even when partly wetted with water. Any source of ignition, such as friction, heat, sparks, or flame, may cause fire or explosion in the substance. DICHAN is chemically unstable in the presence of incompatible materials such as oxidizing agents, bases, and strong reducing agents (Valdez-Salas et al., 2020). DICHAN was therefore given a score of 3 and 1 for flammability and reactivity.

Potassium silicate has no known reactive hazards and is stable under normal conditions. The substance is noncombustible with unavailable information on its flash point, autoignition temperature, and explosion limits (Weldes & Lange, 1969). Potassium silicates were therefore given a score of 0 for both flammability and reactivity.

In terms of flammability, DICHAN ranked the highest, followed by phosphate esters. In terms of chemical reactivity, phosphate esters ranked the highest, followed by sodium bisulfite. Sodium molybdate and potassium silicate are the least dangerous substances in terms of both flammability and reactivity, which both scored zero.

The overall safety sub-index percentages of the five studied corrosion inhibitors (based on their given scores) are illustrated in Fig. 2.

Table 3: Safety sub-index scores

Corrosion inhibitors	Safety issues	
	Flammability Score	Chemical reactivity Score
Sodium molybdate	0	0
Sodium bisulfite	0	2
Phosphate ester	2	3
Dicyclohexylamine nitrite	3	1
Potassium silicate	0	0

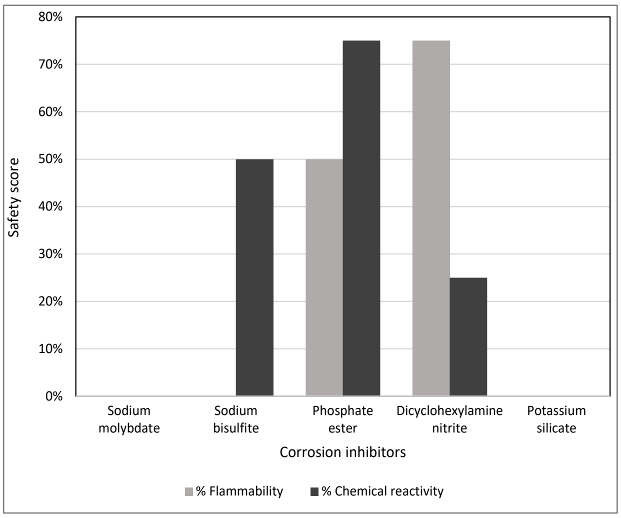

Fig 2: Safety sub-index percentages

3.2 Results and discussion for Health Sub-Index

The health sub-index scores of all five corrosion inhibitors are given in the aspect of exposure routes which are eyes, inhalation, and skin. The scores are tabulated in Table 4.

Sodium molybdate is not classified as a hazardous substance and does not require specific label elements. However, it is advisable that generic measures should be applied when handling any chemical substances. This includes wearing suitable personal protective equipment, having adequate air circulation, thoroughly washing or flushing the skin or eye when in contact, and seeking medical attention if unwell after exposure (Shams El Din & Wang, 1996). Sodium molybdate was given scores of 0 for all three health sub-indexes as shown in Table 4.

Sodium bisulfite is a white crystalline powder with a slight sulphurous odour (Aguilar et al., 2016). The solutions may release toxic and hazardous fumes of sulphur oxides, including sulphur dioxide. It is also reported as a strong irritant to skin and tissue (Nikolaeva & Khusnutdinova, 2021). Its hazard statements are H319 (causes serious eye irritation), H302 (harmful if swallowed), and H313 (may be harmful to skin). According to GHS classification, it is a Category 4 acute oral toxicity, Category 5 acute dermal toxicity, and Category 2A serious eye irritant. Due to these classifications and statements, sodium bisulfite scores highly for hazardous exposure through the eyes, moderately hazard through oral/respiratory routes, and lowly hazardous score through dermal contact which corresponds to the values 3, 2, and 1 as shown in Table 3.

Table 4: Health sub-index scores

Corrosion inhibitor	Exposure route	Hazard	Score
Sodium molybdate	Eyes	NA	0
	Oral/Respiratory	NA	0
	Dermal	NA	0
Sodium bisulfite	Eyes	H319	3
	Oral/Respiratory	H302	2
	Dermal	H313	1
Phosphate ester	Eyes	H318	2
	Oral/Respiratory	NA	0
	Dermal	H315	2
DICHAN	Eyes	NA	1
	Oral/Respiratory	H302, H332	2
	Dermal	GHS07	1
Potassium silicate	Eyes	H318	2
	Oral/Respiratory	H335	3
	Dermal	H315	2

Phosphate esters such as mono and di-phosphate esters are categorised under Category 2 (H315) for skin corrosion or irritant, and Category 1 (H318) for serious eye damage or irritant. Both exposure routes through the eyes and skin were given score of 2. No classifications were given for oral ingestion and inhalation therefore a score of 0 was given to this sub-index. General skin and body protection such as gloves and protective clothing should be worn when handling the substance (Shi et al., 2020).

Contact with DICHAN may cause irritation to the skin, eyes, and mucous membranes as well as it is toxic by ingestion. Hazard statements for this substance include H302 (harmful if swallowed), H332 (harmful if inhaled), and classified as irritant GHS07. include H302 (harmful if swallowed), H332 (harmful if inhaled), and classified as irritant GHS07.

Potassium silicate hazard statements include H318 (Category 1) which causes serious eye damage or irritation, H315 (Category 2) which causes skin irritation, and H335 (Category 3) which targets specific organs (respiratory system). Precautionary statements include P262 (Do not get in eyes, on the skin, or on clothing), and P280 (Wear protective gloves/protective clothing/eye protection/face protection).

The given safety scores were converted to percentages and plotted in a bar chart shown in Fig 3. The chart clearly shows that sodium molybdate is the

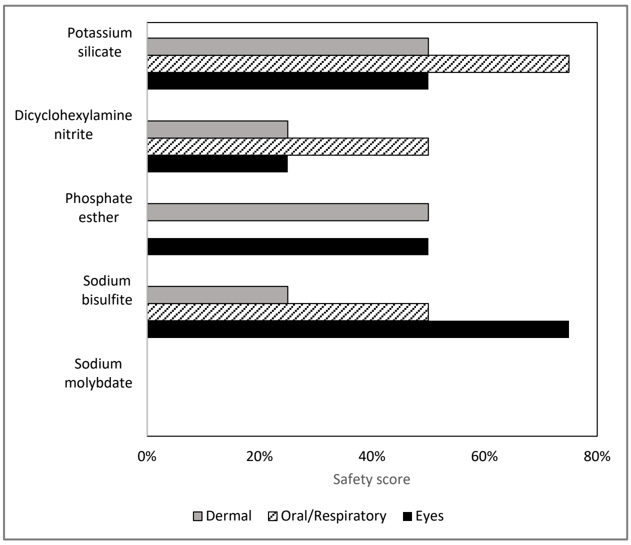

Fig 3: Percentage of health sub-index scores

least hazardous compound in this study. The most hazardous eye-irritant is sodium bisulfite, while the most hazardous in terms of oral ingestion or inhalation is potassium silicate.

It can be concluded that the most hazardous exposure pathway for corrosion inhibitors to its user is through eye contact and via oral ingestion or inhalation. Special precautions must be taken when handling these chemical products. It is important to note that all ratings in this study were made through the judgment of the authors and with extensive analysis of the safety data sheets of all corrosion inhibitors.

4.0 Conclusions

In conclusion, the evaluation of the safety and health concerns of the chemical compounds used in corrosioninhibitors that were implemented based on the Product Safety and Health Index (PSHI) was accomplished successfully. The outcome proved that the index-based method can be utilised to pinpoint the possible sources of safety and health risk from exposure to corrosion inhibitors. Additionally, the score that the substances received will be used as a reference to establish the danger level for each sub-index. The evaluation could be expanded to include other types of formulated items such as detergents and cosmetics in future research. Based on the safety sub-index, it was concluded that sodium molybdate and potassium silicate were the safest corrosion inhibitors based on their scores of zero for both flammability and chemical reactivity. On the other hand, the health sub-index scores revealed that only sodium molybdate is the safest corrosion inhibitor. Although this work was intended to assess the safest and minimal health effects on employees, all corrosion inhibitors have their own benefits and drawbacks. The selection of the most appropriate corrosion inhibitor is subjected to its application, cost, environmental effects and safety and health factors.

Authorship contribution statement

Siti Rafidah Ab Rashid: Visualisation, Investigation, Supervision, Validation, Writing-Reviewing and Editing. **Mohamad Khairul Anwar Mohamad Rasidin**: Data curation, Writing-Original draft preparation. **Nor Roslina Rosli**: Conceptualisation, Methodology, Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The highest appreciation goes to the technical staff of Drilling Lab, College of Engineering, UiTM Shah Alam for the technical support offered in completing this work.

References

Aguilar, F., Crebelli, R., Domenico, A. di, Dusemund, B., Frutos, M. J., Galtier, P., Gott, D., Gundert-Remy, U., Lambré, C., Leblanc, J.-C., Lindtner, O., Moldeus, P., Mortensen, A., Mosesso, P., Parent-Massin, D., Oskarsson, A., Stankovic, I., Waalkens-Berendsen, I., Woutersen, R. A...Tard, A. (2016). Scientific Opinion on the re-evaluation of sulfur dioxide (E 220), sodium sulfite (E 221), sodium bisulfite (E 222), sodium metabisulfite (E 223), potassium metabisulfite (E 224), calcium sulfite (E 226), calcium bisulfite (E 227) and potassium bisulfite (E 228) as food additives. *EFSA Journal*, *14*(4), 4438. https://doi.org/10.2903/J.EFSA.2016.4438

Alink, B. A., Outlaw, B., Jovancicevic, V., Ramachandran, S., & Campbell, S. (1999, April). *Mechanism of CO_2 corrosion inhibition by phosphate esters* [Paper presentation]. CORROSION 99, San Antonio, Texas, USA.

Andersen, F. A. (2001). Final report on the safety assessment of sodium metaphosphate, sodium trimetaphosphate, and sodium hexametaphosphate. *International Journal of Toxicology*, *20 Suppl 3* (SUPPL. 3), 75–89. https://doi.org/10.1080/10915810152630756

Askari, M., Aliofkhazraei, M., Jafari, R., Hamghalam, P., & Hajizadeh, A. (2021). Downhole corrosion inhibitors for oil and gas production–A review. *Applied Surface Science Advances*, *6*, 100128. https://doi.org/10.1016/J.APSADV.2021.100128

Aslam, J., Aslam, R., Basik, M., & Verma, C. (2021). Corrosion inhibitors for crude oil refinery units. In C. M. Hussain & C. Verma (Eds.). *Sustainable corrosion inhibitors I: Fundamentals, methodologies, and industrial applications.* (pp. 207–221). ACS Symposium Series 1403, American Chemical Society. https://doi.org/10.1021/BK-2021-1403.CH010

Baalisampang, T., Abbassi, R., & Khan, F. (2018). Overview of marine and offshore safety. In F. Khan & R. Abbassi (Eds.), *Methods in chemical process safety.* (pp. 1–97). Elsevier. https://doi.org/10.1016/BS.MCPS.2018.04.001

Cao, H., Liu, J., Zhuang, Y., & Glindemann, D. (2000). Emission sources of atmospheric phosphine and simulation of phosphine formation. *Science in China Series B: Chemistry*, *43*(2), 162–168. https://doi.org/10.1007/BF03027306

Cox, J. R., & Ramsay, O. B. (1964). Mechanisms of nucleophilic substitution in phosphate esters. *Chemical Reviews*, *64*(4), 317–352. https://doi.org/10.1021/CR60230A001/ASSET/CR60230A001.FP.PNG_V03

Diamantino, T. C., Guilhermino, L., Almeida, E., & Soares, A. M. V. M. (2000). Toxicity of sodium molybdate and sodium dichromate to daphnia magna straus evaluated in acute, chronic, and acetylcholinesterase inhibition Tests. *Ecotoxicology and Environmental Safety*, *45*(3), 253–259. https://doi.org/10.1006/EESA.1999.1889

Gao, X., Abdul Raman, A. A., Hizaddin, H. F., Bello, M. M., & Buthiyappan, A. (2021). Review on the inherently safer design for chemical processes: Past, present and future. *Journal of Cleaner Production*, *305*, 127154. https://doi.org/10.1016/J.JCLEPRO.2021.127154

Haldhar, R., Kim, S. C., Berdimurodov, E., Verma, D. K., & Hussain, C. M. (2021). Corrosion inhibitors: industrial applications and commercialization. In C. M. Hussain & C. Verma (Eds.), *Sustainable corrosion inhibitors II: Synthesis, design, and practical applications* (pp. 219–235). *ACS Symposium Series*, American Chemical Society. https://doi.org/10.1021/BK-2021-1404.CH010

Hassim, M. H., & Hurme, M. (2010). Inherent occupational health assessment during process research and development stage. *Journal of Loss Prevention in the Process Industries*, *23*(1), 127–138.

Hou, B., Li, X., Ma, X., Du, C., Zhang, D., Zheng, M., Xu, W., Lu, D., & Ma, F. (2017). The cost of corrosion in China. *npj Materials Degradation*, *1*(1), 1–10. https://doi.org/10.1038/s41529-017-0005-2

Koch, G. (2017). Cost of corrosion. In A. M. El-Sherik (Ed.), *Woodheads publishing series in energy, trends in oil and gas corrosion research and technologies: Production and transmission* (pp. 3–30). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-101105-8.00001-2

Ma, I. A. W., Ammar, S., Kumar, S. S. A., Ramesh, K., & Ramesh, S. (2021). A concise review on corrosion inhibitors: types, mechanisms, and electrochemical evaluation studies. *Journal of Coatings Technology and Research,* *19*(1), 241–268. https://doi.org/10.1007/S11998-021-00547-0

Md, N., Faizah, S., & Majid, A. (2019). Effectiveness of Construction safety hazards identification in virtual reality learning environment. *Environment-Behaviour Proceedings Journal*, *4*(12), 375–381. https://doi.org/10.21834/E-BPJ.V4I12.1802

Nair, B., & Elmore, A. (2003). Final report on the safety assessment of sodium sulfite, potassium sulfite, ammonium sulfite, sodium bisulfite, ammonium bisulfite, sodium metabisulfite and potassium metabisulfite. *International Journal of Toxicology*, *22 Suppl 2*(SUPPL. 2), 63–88. https://doi.org/10.1080/10915810305077X

Nikolaeva, L. A., & Khusnutdinova, E. M. (2021). Treatment of gas emissions of sodium bisulfite production to remove sulfur dioxide by pelletized sorption material. *Chemical and Petroleum Engineering* *56*(11), 935–942. https://doi.org/10.1007/S10556-021-00865-5

Prasad, A.R., Kunyankandy, A. and Joseph, A. (2020). Corrosion inhibition in oil and gas industry: economic considerations. In V. S. Saji & S. A. Umoren (Eds.), *Corrosion inhibitors in the oil and gas industry*. (pp. 135–150). Wiley. https://doi.org/10.1002/9783527822140.ch5

Raja, P. B., Ismail, M., Ghoreishiamiri, S., Mirza, J., Ismail, M. C., Kakooei, S., & Rahim, A. A. (2016). Reviews on corrosion inhibitors: A short view. *Chemical Engineering Communications, 203*(9), 1145–1156. https://doi.org/10.1080/00986445.2016.1172485

Ranjith, A., Balaji Rao, K., & Manjunath, K. (2016). Evaluating the effect of corrosion on service life prediction of RC structures–A parametric study. *International Journal of Sustainable Built Environment*, *5*(2), 587–603. https://doi.org/10.1016/J.IJSBE.2016.07.001

Raslan, R., Hassim, M. H., Chemmangattuvalappil, N. G., Ng, D. K. S., & Ten, J. Y. (2020). Development of inherent safety and health index for formulated product design. *Journal of Loss Prevention in the Process Industries*, *66*, 104209. https://doi.org/10.1016/J.JLP.2020.104209

Shams El Din, A. M., & Wang, L. (1996). Mechanism of corrosion inhibition by sodium molybdate. *Desalination*, *107*(1), 29–43. https://doi.org/10.1016/0011-9164(96)00148-8

Shi, F., Liang, K., Liu, R., Dong, Q., He, Z., Xu, J., & Liu, J. (2020). Elevated occupational exposure to chlorinated phosphate esters at a construction materials manufacturing plant. *Environment International*, *139*, 105653. https://doi.org/10.1016/J.ENVINT.2020.105653

Tamalmani, K., & Husin, H. (2020). Review on corrosion inhibitors for oil and gas corrosion issues. *Applied Sciences,* *10*(10), 3389. https://doi.org/10.3390/APP10103389

Tang, Z. (2019). A review of corrosion inhibitors for rust preventative fluids. *Current Opinion in Solid State and Materials Science*, *23*(4), 100759. https://doi.org/10.1016/J.COSSMS.2019.06.003

Topçu, İ. B., & Uzunömeroğlu, A. (2020). Properties of corrosion inhibitors on reinforced concrete. *Journal of Structural Engineering & Applied Mechanics*, *3*, 93–109. https://doi.org/10.31462/jseam.2020.02093109

Tristijanto, H., Ilman, M. N., & Tri Iswanto, P. (2020). Corrosion inhibition of welded of X–52 steel pipelines by sodium molybdate in 3.5% NaCl solution. *Egyptian Journal of Petroleum*, *29*(2), 155–162. https://doi.org/10.1016/J.EJPE.2020.02.001

Tuma, D. (2020). Research Laboratory: Fire, Explosion, and Life Safety Analysis. *Fire Protection Engineering: Culminating Experience Project Reports*. https://digitalcommons.calpoly.edu/fpe_rpt/127

Valdez-Salas, B., Schorr-Wiener, M., & Cheng, N. (2020). Vapor phase corrosion inhibitors for oil and gas field applications. In V.S. Saji & S.A. Umoren (Eds.), *Corrosion inhibitors in the oil and gas industry* (pp. 339–357). Wiley. https://doi.org/10.1002/9783527822140.CH14

Vorobyova, V., Chygyrynets', O., Skiba, M., Zhuk, T., Kurmakova, I., & Bondar, O. (2018). A comprehensive study of grape pomace extract and its active components as effective vapour phase corrosion inhibitor of mild steel. *International Journal of Corrosion and Scale Inhibition*, *7*(2), 185–202. https://doi.org/10.17675/2305-6894-2018-7-2-6

Vukasovich, M. S., & Robitaille, D. R. (1977). Corrosion inhibition by sodium molybdate. *Journal of the Less Common Metals*, *54*(2), 437–448. https://doi.org/10.1016/0022-5088(77)90066-2

Warnasooriya, S., & Gunasekera, M. Y. (2017). Assessing inherent environmental, health and safety hazards in chemical process route selection. *Process Safety and Environmental Protection*, *105*, 224–236. https://doi.org/10.1016/J.PSEP.2016.11.010

Weldes, H. H., & Lange, K. R. (1969). Properties of soluble silicates. *Industrial and Engineering Chemistry*, *61*(4), 29–44. https://doi.org/10.1021/IE50712A008/ASSET/IE50712A008.FP.PNG_V03

Winder, C., Azzi, R., & Wagner, D. (2005). The development of the globally harmonized system (GHS) of classification and labelling of hazardous chemicals. *Journal of Hazardous Materials*, *125*(1–3), 29–44. https://doi.org/10.1016/J.JHAZMAT.2005.05.035

Yan, C., Young, R., Espin, C., Wei, W., Wang, W., & Nix, D. (2022, June 20–22). *Corrosion Inhibitor Evaluation and Selection for Shale & Tight Corrosion Control* [Paper presentation]. SPE/AAPG/SEG Unconventional Resources Technology Conference, Houston, Texas, USA. https://doi.org/10.15530/URTEC-2022-3722241

Yazid, M. F. H. A., Ta, G. C., & Mokhtar, M. (2020). Classified chemicals in accordance with the globally harmonized system of classification and labeling of chemicals: comparison of lists of the European Union, Japan, Malaysia and New Zealand. *Safety and Health at Work*, *11*(2), 152–158. https://doi.org/10.1016/J.SHAW.2020.03.002

Ying So, W., Hassim, M. H., Ahmad, S. I., & Rashid, R. (2021). Inherent occupational health assessment index for research and development stage of process design. *Process Safety and Environmental Protection*, *147*, 103–114. https://doi.org/10.1016/J.PSEP.2020.09.015

Zainal Abidin, M., Rusli, R., Khan, F., & Mohd Shariff, A. (2018). Development of inherent safety benefits index to analyse the impact of inherent safety implementation. *Process Safety and Environmental Protection*, *117*, 454–472. https://doi.org/10.1016/J.PSEP.2018.05.013

Zehra, S., Mobin, M., & Aslam, R. (2022). Corrosion prevention and protection methods. *Eco-Friendly Corrosion Inhibitors*, 13–26. https://doi.org/10.1016/B978-0-323-91176-4.00023-4

Zhu, J., Liu, Z., Cao, Z., Han, X., Hao, L., & Wei, H. (2022). Development of a general inherent safety assessment tool at early design stage of chemical process. *Process Safety and Environmental Protection*, *167*, 356–367. https://doi.org/10.1016/J.PSEP.2022.09.00