ROYAL SOCIETY OF CHEMISTRY

SUSTAINABILITY

Improving performance of sustainable non-metallics solutions for corrosion

A Synergy report

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Our planet faces critical challenges, and at the Royal Society of Chemistry we are uniquely placed to bring together the right people with the right expertise to tackle these challenges. We are particularly proud of our Synergy programme, which places collaboration at the heart of solving key issues facing not just industry but the world as a whole.

In the past year the Synergy programme has been exploring new ways for the chemistry community to tackle corrosion, a multi-industry problem affecting everything from oil and gas pipelines, buildings and infrastructure and manufacturing. Non-metallics could present a sustainable solution to this problem as an alternative to metals, which are highly susceptible to corrosion. Chemistry has a great deal to offer in this area – helping to improve the performance of non-metallics and enabling many industries to adopt these materials.

This report is the output of recent workshops that brought together experts from industry and academia. I am proud to be able to share this report with the wider community, with the aim of sparking further development in this crucial area.

JO REYNOLDS
Director of Science and Communities, Royal Society of Chemistry

This report succinctly summarises the current state of the art, the challenges and the opportunities that are presented by using non-metallic materials to replace current infrastructure making it more durable and less costly to maintain, whilst recognising the importance of the principles of sustainability and circularity.

The cross-sector application of non-metallic materials for durable, light-weight and corrosion resistant structural components is at the heart of the mission of the National Composites Centre, as is the need for such materials and products to be sustainable. The National Composites Centre looks forward to collaborating with the Royal Society of Chemistry to deliver the recommendation of this important report.

RICHARD OLDFIELD
Chief Executive of the National Composites Centre

Contents

1

Executive summary

Non-metallics could transform the way that industry deals with corrosion, enabling businesses to transition from corrosion control to corrosion prevention strategies. Developing sustainable non-metallic solutions may reduce long-term corrosion costs for businesses, significantly benefitting the global economy. Cross-industry collaboration has the potential to build on existing chemical science knowledge within this topic and generate solutions that will benefit multiple industries and sectors. Without collaboration, individual businesses could face longer timeframes and higher costs for innovation.

Corrosion costs the global economy 2.5 trillion USD each year (£1.9 trillion), which is equivalent to 3.4% GDP. Businesses use corroding materials like iron and steel in components, products and infrastructure across many applications, but the industry contributes significantly to global CO_2 emissions. It is not sustainable – environmentally or economically – to continue using these corroding materials at the current rate. Regulation may also increase urgency for businesses to find new sustainable solutions for corrosion. Non-metallics could offer a solution for replacing and protecting existing corroding metals, but currently they are too risky for industry to adopt.

The Royal Society of Chemistry brought together a diverse group of experts representing independent and governmental technology organisations and multiple industries and sectors. Together we identified two opportunities to improve the performance of non-metallics and build industry's confidence in adopting sustainable solutions for corrosion:

1. **Knowledge framework** to develop fundamental understanding, standardise characterisation and testing methods, and predict performance.
2. **Circularity projects** to deliver manufacturing and recycling processes that ensure existing and new non-metallic solutions are sustainable.

Collaboration is essential for developing these opportunities. It can de-risk the economic burden of research and development, reduce the potential for duplicating work and leverage multidisciplinary skills to deliver solutions faster. Key findings from this work highlight the need for cross-industry collaboration to advance our understanding, deliver solutions that build confidence in multiple industries, and influence key areas of funding, regulation and policy that could support innovation.

Recommendations made by participants to progress these opportunities are:

1. Validate findings with more industries and supply chains
2. Gain a baseline understanding of current relevant work in this area
3. Initiate cross-industry knowledge sharing and networking to define focus areas

Improving the performance of non-metallic solutions for corrosion presents a significant opportunity for the UK chemical science community to collaborate. Involvement in the Royal Society of Chemistry's Synergy programme will enable businesses to build relationships with a wide network of academics and other companies concerned with this topic, advance knowledge required to find solutions and gain external support for innovation.

In 2020, we are seeking input from businesses operating across the supply chain, independent and government funded research and technology organisations, and experts in academia to continue developing the opportunities for collaboration in this report.

2

Definitions

In this report, we refer to the following definitions:

Circular economy	Alternative to linear economy in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.
Chemical science community	The Royal Society of Chemistry represents a network of individuals and businesses that are concerned with advancing the chemical sciences for the benefit of humanity. The community consists of experts from academia, business and government organisations.
Corrosion	Corrosion is a naturally occurring deterioration of a metal that results from a chemical or electrochemical reaction with its environment.
Industry	The companies that participated in the Synergy workshops (see 9.2 Participating organisations) as well as the supply chains and sectors they represent.
Non-metallics	The generic term given to anything not made from metals.
Non-metallic material	Materials not made from metals that are used as structures or components in products. We specifically refer in the report to non-metallic materials that could replace existing corroding metals, e.g. composites, polymers, ceramics, glass, cementitious materials.
Non-metallic coating	Materials not made from metals that can be applied to a surface of an object for decoration and/or functionality. In this report, we refer to non-metallic coatings as materials that can protect corroding metals, e.g. organic or inorganics
Sustainable material	A material that is designed to limit consumption of non-renewable resources and reduce adverse impact on the environment when used, e.g. a material that is produced from non-virgin feedstocks, doesn’t release toxic chemicals into the environment and can be recycled after use.
Sustainable product	A product that provides environmental, social and economic benefits whilst protecting public health and the environment, e.g. lightweight wing that reduces overall CO_2 emissions of aeroplanes.

3

Background

3.1 Topic

Corrosion is a natural process that converts metal into a more chemically stable form, leading to material deterioration.[2] It is a complex phenomenon, often influenced by multiple chemical and mechanical factors including temperature, pressure and microbial activity.

The estimated global cost of corrosion is 2.5 trillion USD each year (£1.9 trillion), which is equivalent to 3.4% GDP.[1] In 2018, we produced 1,809 million tonnes of potentially corroding iron and steel globally, and our demand is increasing.[3]

Each year industry spends $1.2 trillion on methods to control corrosion using protective coatings, resistant materials, corrosion inhibitors and cathodic protection. However, as metals are thermodynamically unstable, we are only able to delay the process, not fully stop it.[4]

Material degradation caused by corrosion can result in plant shutdowns, valuable resource wastage, product loss or contamination, efficiency reductions, costly maintenance, health and safety risks, and expensive overdesign. Controlling corrosion is a costly undertaking for industry, but it can slow down innovation and technological progress too.

At the same time, businesses are proactively integrating sustainability principles in their products and their organisations.[5] UN Sustainable Development Goals are also putting increasing pressure on countries to produce and consume materials responsibly, tackle climate change and protect public health and the environment.[6]

Corrosion is a significant burden on the economy. The costs associated with the ongoing repair and replacement of corroded steel are extreme, and are rapidly becoming unacceptable in today's world where sustainability is a priority. Industry recognises that the relative chemical inertness of non-metallics could offer a way to reduce the negative impacts of corrosion. However, there is a great need for more research into this area, as the available technology is not yet mature enough for industry to exploit commercially.[11]

Industry are already using non-metallics in coatings, components and structures to improve product performance in specific markets. The automotive industry, for example, are using higher volumes of plastics in cars to reduce weight and decrease CO_2 emissions.[7] Similarly, the construction industry uses fibre-reinforced concrete to improve durability.[8] The chemical science community recognises that we could be missing opportunities to exploit knowledge and technology from other applications and integrate corrosion resistance into the design of non-metallics.

Developing new solutions to avoid corrosion could transform industry's traditional approach to corrosion management, ultimately enabling faster innovation and significant long-term economic benefits to multiple industries.

3.2 Scope

Sustainable non-metallics could eliminate corrosion and bring major benefits to industry and the global economy. However, it is a multi-faceted long-term challenge too complex and risky for any single organisation to solve alone.

Collaborative research and development projects, technology licensing and PhD research projects with academic institutions can help industry de-risk specific technical challenges in the short-term. However, before businesses can adopt non-metallics for avoiding corrosion in the markets they operate in, they need a high-level of confidence in how these materials will perform throughout their lifetime.

This challenge is not specific to a single industry or company and therefore presents an opportunity for cross-industry collaboration to reduce overall risks.

Industry recognises that tackling such a challenge requires collaboration across the supply chain, multidisciplinary research and development efforts, and appropriate policies and regulations to enable adoption. However, collaborations of this nature do not happen spontaneously – it requires strategic planning and coordination to enable partnerships between many stakeholders that deliver long-term benefits for all.

There are some examples of work already going on in this area. The Non-Metallic Innovation Centre is an example of a collaboration between TWI, Saudi Aramco and the Abu Dhabi National Oil Company to advance non-metallic solutions in the oil and gas industry.[9] The Composites Leadership Forum also highlights the importance of collaboration with the chemicals sector to develop new and existing composites.[10]

Our work identifies a new opportunity for cross-industry collaboration to improve confidence in non-metallic materials that builds on and complements existing efforts. In this work, we explore the chemical-science related challenges that if solved, would improve the through-life performance of non-metallic coatings and materials for avoiding corrosion. Experts highlighted the opportunity to build on existing knowledge and develop new chemical-science based solutions.

The timeframe that we are exploring for this effort is 25 years, from 2020 to 2045, to ensure that we take into consideration the long timeframes associated with developing and adopting technology for different markets.

The scope of this work explores both sustainable non-metallic coatings for protecting corroding metals and sustainable non-metallic materials for replacing corroding metals, with the aim of avoiding corrosion altogether. The corrosion community recognises that this is a considerable challenge that needs to evaluate how new solutions compare to existing materials' performance, properties and sustainable production, and end-of-life strategies.[11]

4

Trends and drivers

This section summarises the current and future trends that could be driving industry to adopt sustainable non-metallics for avoiding corrosion. Using methodology outlined in section 9.1, we analyse the political, economic, social, technological, legal and environmental factors that workshop participants highlighted.

In this section, we discuss how public perception and environmental awareness, future regulatory changes, climate change, advancements in key technologies and business requirements could influence the adoption of non-metallics as solutions to corrosion.

4.1 Societal and environmental

Our climate is changing. With global warming likely to reach 1.5°C between 2030 and 2052, we expect that some regions will observe land and ocean temperature extremes, heavy precipitation and precipitation deficits.[12] These factors are likely to affect corrosion rates in certain geographical areas.[13] In situations where corrosion rates are likely to increase, certain industries like construction may explore non-metallic alternatives to reduce the potential risks.

Climate change will likely lead to greater awareness of society's impact on our environment. According to the World Steel Association, we are producing 1.8 billion tonnes of iron and steel globally each year, which is responsible for 24% of the total CO_2 emissions.[3] Studies also estimate that 1% of steel is lost through corrosion, wear and tear.[14] Industry recognises that producing and consuming metals that corrode at this rate may become unacceptable, driving businesses to diversify their material portfolios towards sustainable solutions in the future.

4.2 Economic

Economic factors are also driving industry to explore new solutions, as managing corrosion can be both high-risk and high-cost for businesses. If failures occur due to material degradation, industry may lose product, introduce contaminants into products or shut down plants for repair and maintenance.[15] In serious cases, failures can also lead to catastrophic environmental and health and safety problems, resulting in reputational risk.

Industry currently relies on expensive inspection, monitoring and maintenance regimes to control corrosion. Specialists often over-engineer solutions for additional confidence,[16] and in some markets personnel operate in remote and demanding environments to apply solutions, which both add additional costs. The global cost of controlling corrosion is $1.2 trillion each year. Individual businesses will reduce costs associated with controlling corrosion in their own market to remain competitive; in the future, there may be a bigger drive from industry to explore transformative solutions that could eliminate corrosion costs.

4.3 Technological

As well as economic factors, advances in technology could also drive industry to adopt non-metallics for avoiding corrosion. Advances in technology are already improving current corrosion control regimes. For example, the TRAC-Tec Tool project is developing remote cleaning and inspection for the oil and gas industry, reducing the need for personnel during asset inspection.[17] However, there is broad appreciation in industry that extending the lifetime and performance of small components to major infrastructure could cut long-term costs of corrosion by eliminating the need for inspection and maintenance.

There are already examples where industry is using non-metallics for improving product performance. The aerospace and automotive industries for example are using polymers and polymer composites to make components more light weight – to reduce emissions and fuel consumption.[10] The energy sector also uses composites for their mechanical properties and durability, enabling them to operate in harsher environments in the deep sea.[10] The construction industry are using sustainable coatings to enhance indoor air quality to improve people's wellbeing.[18] Experts recognise that there could be opportunities to exploit existing knowledge and technology from these applications, potentially accelerating the development of sustainable non-metallics for avoiding corrosion.

4.4 Legislative

Regulation and legislation could also influence industry to explore sustainable non-metallics for avoiding corrosion. The UN sustainability development goals are influencing changes in material production and consumption, with 71 countries and the European Union already reporting policy and regulation to reduce material footprints.[19] Steel recycling is one way of reducing waste and emissions but 25.5% of steel is unrecoverable.[20] 88% of the total cost of controlling corrosion is spent on organic coatings, which can contain epoxy resins as film-forming elements. Experts also appreciate that we currently produce a significant proportion of these epoxy-resins from fossil derived feedstocks and they do not easily break down at the end of their life.[21]

We are also seeing environmental regulation and safety legislation restricting the use of certain chemicals used in corrosion management technologies. Industry previously used Hexavalent Chromium as a corrosion inhibitor in protective coatings, but since 2017 it has been restricted under REACH in some industries because of its toxicity. Despite significant research and development over the past 30 years, industry still recognises hexavalent chromium as the benchmark compound for preventing corrosion.[22]

Trends in legalisation tend to increase producer responsibility, increase recycling rates and reduce availability of landfill. There is also a growing emphasis on the circular economy and we are gaining greater understanding of material life cycles and potential health, safety and environmental risks. Industry anticipate that future regulations will drive innovation in this area and require businesses to explore sustainable solutions to corrosion.

5

Gaps and technical challenges

As well as the trends and drivers influencing innovation in this topic, participants also discussed the potential gaps and technical challenges that industry may need to solve to develop non-metallic solutions for corrosion.

This section summarises three gaps in knowledge:

- theoretical understanding of degradation mechanisms;
- standard characterisation and testing methods; and
- techniques to ensure manufacturing, quality assurance and recyclability.

5.1 Theoretical understanding of degradation mechanisms

In a similar way to corrosion in metal, many factors influence the long-term performance and durability of non-metallics. Before industry can explore opportunities to use non-metallic solutions for corrosion, they need to understand the different possible mechanisms of material degradation.

Degradation mechanisms for non-metallic materials do exist.[23] However, current theories may be limited and, without better understanding in this area, we can only go so far to correlate and explain degradation processes in real-life situations. Incorporating more real-world data could improve our understanding of the complex interactions between material surfaces and external environments.

Initially this will be important for better understanding how existing non-metallic coatings and materials perform compared to traditional metals. In the future, experts acknowledge an opportunity to formalise these findings into performance standards for non-metallics to improve confidence.

In the long-term, advancements in this area could also enable the development of new sustainable non-metallic coatings and materials by building lifetime models to predict through-life performance.

5.2 Characterisation methods and performance standards

As well as better fundamental understanding of degradation mechanisms, characterisation methods and robust performance standards are critical for building industry's confidence in adopting non-metallics for avoiding corrosion across different applications.

Chemical processes, techniques and methods for assessing degradation rates, material loss and testing degradation in real non-metallic systems do exist. However, experts highlighted that they are not comprehensive enough, appropriate for specific applications, or standardised. There is wide acknowledgement that performance standards for non-metallics are not as developed as traditional metals, which is a significant barrier for industry to explore new solutions for avoiding corrosion.

Industry recognises that there could be opportunities to improve characterisation processes, which often focus on analysing anomalies. Assessing physical and chemical properties in non-metallics in a more rigorous way could build a greater understanding of material performance across the entire system. A specific area for improvement acknowledged by industry is accelerated test regimes. Industry already uses accelerated testing to predict long-term behaviour, but we observed that this was an area for improvement for non-metallics.[23]

As we build our understanding of theory and real-world situations, experts can develop better methods to characterise and test non-metallic performance. One possible benefit is accurate information for regulatory bodies to develop fit-for-purpose standards, which could ultimately provide industry with a higher level of confidence for adopting non-metallics for corrosion resistance.

Furthermore, modellers could use developments in this area, alongside theory, to design better models for predicting lifetime performance of non-metallics. Ultimately, this could enable industry to select and develop sustainable material alternatives for different systems and environments in the long-term.

5.3 Manufacturing and recycling processes

Circular materials, disassembly, recycling and reuse are well-known concerns for non-metallics widely, especially for composites.[24] Alongside building confidence in non-metallics by improving theoretical understanding of degradation and developing characterisation methods and performance standards, we also need to consider sustainable manufacturing and recycling processes for new corrosion solutions.

Experts highlighted that producing non-metallic materials, like composites, to replace corroding metals is not currently possible at scale and viable cost. There is a need for new processing techniques, scale up and quality assurance to make manufacturing non-metallic materials easier, faster and competitive with traditional metals.

Industry often select non-metallics for their durability and resistance to chemicals and wear, both of which are important for protecting and replacing corroding metals. Some systems use multiple components to provide additionally functionality and strength. However, there is wide acknowledgement that these properties make them challenging to recycle at the end of their life, which could be contributing to their presence in landfill.

Processes for chemically degrading plastics are developing but there are significant gaps in knowledge and technology to enable material degradation by design. Without a full understanding of the materials life cycle, including design; in-life use and performance; and possible re-use opportunities.

5.4 Chemical-science based challenges

After discussing gaps in knowledge and technology across different industries, experts identified three chemical-science based challenges that, if solved, could build confidence in using non-metallics for avoiding corrosion.

These challenges are key topics that concern different industries and therefore provide both opportunities for collaboration and knowledge building in chemistry.

1. **Advancing our understanding of material degradation and methods to characterise performance**

   We need to use chemistry to better understand and define material degradation mechanisms, degradation rates and failure modes across different material systems.

2. **Improving our ability to predict material performance**

   Building on our understanding, chemistry can help us to develop accurate models for predicting performance in non-metallics, enabling industry to better assess and select appropriate solutions for different environments.

3. **Developing materials that are circular by design**

   Chemistry is key to developing sustainable alternatives to corroding metals by introducing circularity principles into non-metallic solutions.

6

Opportunities for cross-industry collaboration

These chemical-science based challenges are highly complex and, through this work, industry recognises that we require long-term collaboration between multiple stakeholders to solve them. Industry also acknowledges that these challenges present an opportunity for cross-industry collaboration, because they are common to businesses operating in different markets.

This section summarises two opportunities for cross-industry collaboration that experts developed in this work. Industry recognises that these opportunities could build on existing knowledge and help develop sustainable non-metallic solutions for corrosion over the next 25 years:

1. A knowledge framework to develop fundamental understanding, standardise characterisation and testing methods, and predict performance.
2. Circularity projects to deliver manufacturing and recycling processes that ensure existing and new non-metallic solutions are sustainable.

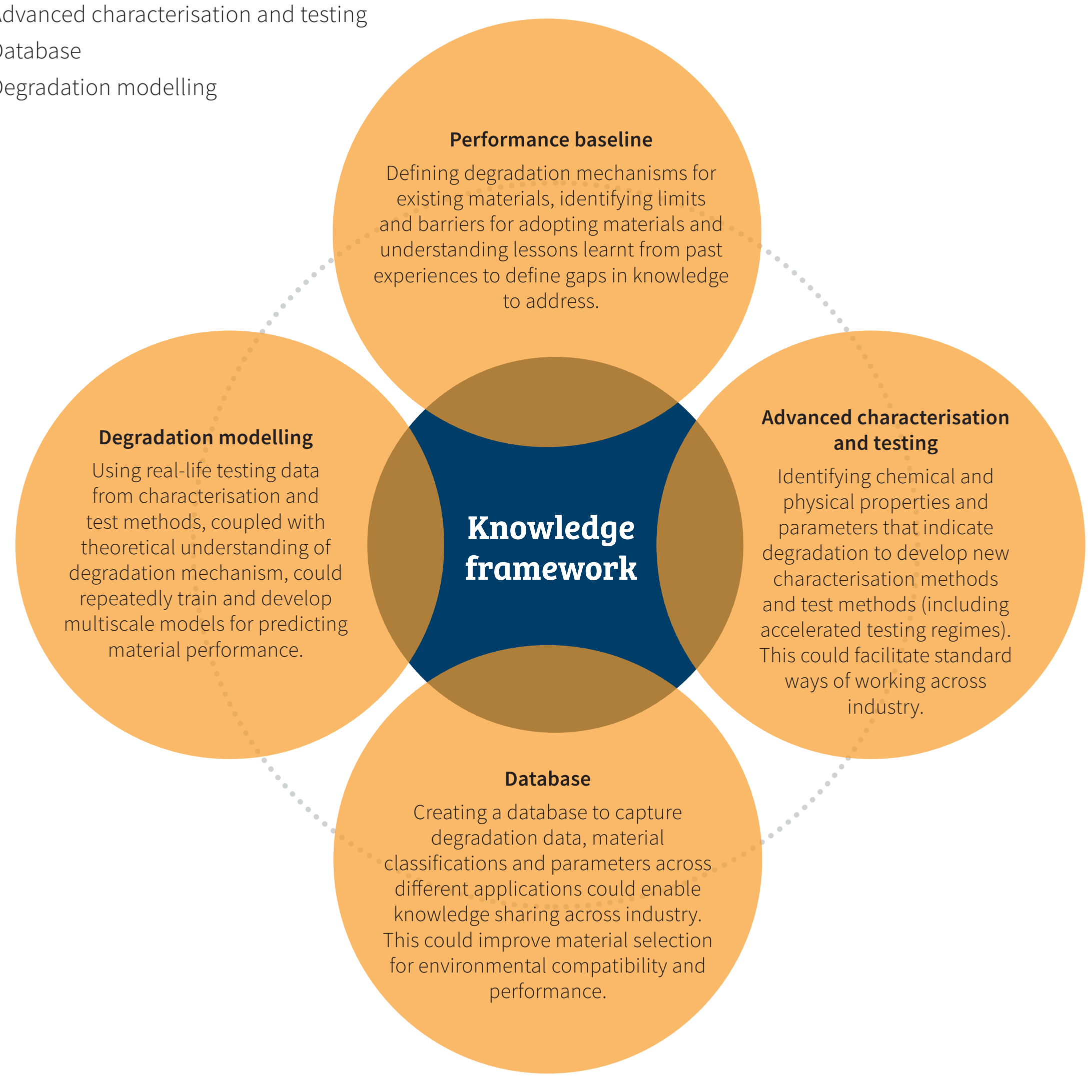
6.1 Knowledge framework

The first opportunity for cross-industry collaboration is a knowledge framework that advances fundamental understanding of degradation processes, improves methods, and develops performance standards for non-metallic corrosion solutions.

Experts recognise that, although knowledge, techniques and processes exists, there are limited mechanisms available for academia and industry to share information on non-metallic performance. Industry identified an opportunity to create a coordinated approach to build on existing chemical-science knowledge in this area and improve confidence in non-metallic coatings and materials for avoiding corrosion.

We identified four key components of this knowledge framework:

1. Performance baseline
2. Advanced characterisation and testing
3. Database
4. Degradation modelling



The framework would:

- provide a basic structure and system for industry to characterise and test materials in real-world situations;
- identify failure modes and develop models for predicting long-term performance in a standardised way;
- build confidence in using non-metallic coatings and materials for avoiding corrosion; and
- increase adoption across applications and markets and develop new supply chains.

Experts recognise that chemistry is a key enabler, but it cannot deliver this opportunity alone. Collaboration with other scientific disciplines, skilled practitioners and businesses from a wide range of industries is critical for building reliable knowledge to advance this area.

Developing a fundamental understanding of degradation processes requires understanding of surface chemistry and complex interactions between materials and the external environment. Collaboration with engineering and biological sciences could bring in additional knowledge about other environmental, mechanical and biological processes affecting corrosion. This could be particularly important for considering how multiple factors influence degradation.

Characterising degradation in non-metallics also requires chemical-science based techniques to assess material properties in real-world situations. Not only is chemistry important for determining the parameters that indicate degradation, experts also appreciate its importance for developing appropriate accelerated test methods for gauging through-life performance in real-world situations.

As theory, methods and techniques become more rigorous and based on real-life data, collaboration with modellers will facilitate the design of reliable models for predicting through-life performance. Sharing chemical data and information would further enable industry to select and design new materials that are appropriate for different applications.

6.2 Circularity projects

The second opportunity for cross-industry collaboration is the need to enable sustainable production and recycling process for non-metallics.

Experts recognise that if industry adopts non-metallic coatings and materials for avoiding corrosion across wide applications, they must also be sustainable. Industry currently sources a high proportion of non-metallics from fossil-derived feedstocks, which often enter landfill at the end of use. Non-metallics based on linear supply chains, that follow a ‘take, make and dispose’ economy, may become unacceptable to society in the near future.

However, there are currently limited processes available for developing closed looped systems for non-metallics that also meet quality assurance. Industry identified two collaborative project opportunities that could develop processes for sustainably producing and manufacturing non-metallics and enable reuse at the end of life.

Ultimately, these could lead to solutions that provide through-life corrosion resistance and meet sustainability criteria.

Two projects that could help industry transition to new non-metallics that provide sustainable corrosion solutions are:

1. Developing reuse options for non-metallics in existing products, assets and infrastructures.
2. Developing new materials that are circular by design.

We identified three work streams that will be important for delivering these projects:

1. Decommissioning and manufacturing processes.
2. Alternative feedstocks.
3. Chemistry toolbox.

The first work stream would develop parallel decommissioning and manufacturing processes. These could offer reuse options for existing non-metallics at the end of their life, address recyclability concerns and avoid large volumes in landfill. Non-metallic material recovery and subsequent conversion into feedstocks for other applications at scale would also maximise the material value in line with circular economy principles.

At the same time, the second work stream would develop alternative feedstocks from non-fossil derived sources so that industry could develop new non-metallics that are sustainable by design. Advancements in this area could create a portfolio of commercially available sustainably produced non-metallics that reduce our reliance on finite hydrocarbon sources. Alongside developments from the first work stream, designers could incorporate degradation processes into new materials so that they degrade at the end of their lifetime.

Underpinning both these work streams is a chemistry toolbox. Developing general techniques, processes and chemical information could facilitate knowledge sharing between industries, which could accelerate the transition from existing methods to new sustainable non-metallic solutions for avoiding corrosion. Potential focus areas for the toolbox include:

- Life cycle analysis and component composition studies to identify potential reuse opportunities for existing non-metallic materials.
- Material traceability and separation techniques for recovering and decommissioning existing non-metallics.
- Manufacturing processes that provide quality assurance and engineering validation of new materials.
- Chemical techniques that enable degradation by design.
- Chemical information about properties of alternative non-fossil derived feedstocks for creating new-materials with comparable or better performance to existing materials.

These projects would:

- Develop new technology for enabling material degradation that could be applied to existing infrastructure and the design of new materials.
- Identify alternative sustainable feedstocks with comparable or better performance than traditional coatings and metals.
- Develop alternative routes to landfill that maximise the value of materials at end-of-life.
- Create new supply chains based on circular economy principles.

7

Collaboration enablers

The two opportunities for cross-industry collaboration developed by experts aim to improve the through-life performance of sustainable non-metallic materials and increase industry's confidence in adopting them for avoiding corrosion. However, these are long-term areas of development that require significant buy-in from across the supply chain, a baseline understanding of current knowledge and appropriate mechanisms to enable knowledge sharing and collaboration.

Through this work, we identified five key areas that will be important for enabling collaboration.

7.1 Supply chain buy-in

Both knowledge framework and circularity project opportunities require action from the entire supply chain including manufacturers, designers, end-users, waste management organisations, and regulatory and standards bodies. To deliver advancements in these areas will require industry to adopt a new mindset for sharing data and knowledge, collaborating with competing and non-competing businesses and interacting with stakeholders across the entire system

A selection of these stakeholders have contributed to this initial piece of work, but industry recognises that wider support and early buy-in from organisations across the entire supply chain are needed to progress these opportunities.

7.2 Problem definition

The opportunities identified so far are high-level and we need to define specific projects that industry can work on collaboratively to initiate any action. Encouraging key stakeholders to share knowledge about key materials, applications and lessons learnt would enable industry to define common challenges to focus on initially.

While some activities such as the Defence Academic Pathways[25] and Composites Leadership Forum10 are facilitating collaboration in areas related to this topic, there are currently limited opportunities for different industries and their supply chains to share knowledge and define specific cross-industry problems that they can work on collaboratively.

7.3 Collaboration with other disciplines

This work focuses on chemical-science related opportunities for collaboration. While there is an appreciation that chemistry is important in delivering each of these opportunities, experts highlighted the importance of working across disciplines, especially at the research and early technology development stages.

Collaboration with engineering, biological sciences and modelling will especially be important for delivering solutions and scaling them up. Industry recognises that sharing knowledge between key disciplines at an early stage will be important for defining short-term specific interdisciplinary research projects and long-term areas for collaboration.

7.4 Current state of information

Throughout this work we drew on knowledge from different industries and disciplines, but in order to progress these opportunities, we need a detailed understanding of what information exists currently. We know that knowledge exists in silos because it is challenging for different industries to share information outside of their organisation or sector.

We also know that relevant work is taking place on degradation mechanisms in coatings and composites, and on applying circular economy principles to non-metallics.

Industry recognises that getting a baseline understanding of the work going on in this area would help identify developments that complement our focus and identify gaps we need to address.

7.5 Funding mechanism for collaboration

The final enabler for collaboration is funding. Through this work, experts highlighted the importance of funding at all scales and timeframes to initiate and sustain collaboration. Initially small scale public funding can coordinate early stage knowledge sharing and problem definition. Large scale funding would ultimately de-risk longer-term collaborative projects around data sharing and scale-up.

8

Conclusions and recommendations for next steps

In this report, we discussed the initial findings on cross-industry opportunities for collaboration over the next 25 years to increase industry's confidence in adopting non-metallics for avoiding corrosion. Experts in academia and industry identified two opportunities in chemistry that could transform the way that industry could use non-metallic coatings and materials to avoid corrosion in a sustainable way:

1. Knowledge framework to develop fundamental understanding, standardise characterisation and testing methods and predict performance of non-metallics.
2. Circularity projects to deliver manufacturing and recycling processes that ensure existing and new non-metallic solutions are sustainable.

We identified a sizeable opportunity to build on existing chemical science knowledge to advance this topic through collaboration. We know that current knowledge and technology exists for understanding degradation mechanisms in non-metallics and characterising chemical and physical properties to identify and test degradation. However, advances in chemistry that incorporate real-world data and standardisation across industry could significantly improve the reliability of models to predict performance in non-metallics.

We also know that chemistry will play a huge part in ensuring that we develop and design new non-metallics that are sustainable, by developing alternative feedstocks and end-of-life options based on circular economy principles.

Opportunities outlined in this report could not only create sustainable solutions for corrosion based on non-metallics, they could also significantly improve industry's confidence in adopting them across wide applications and at scale. Ultimately, developments in this area could have a positive impact on the economy and our environment by significantly reducing the global cost of corrosion, lowering the associated risks of corrosion when failures occur and contributing to the transition to a circular economy.

We recognise that no single organisation can deliver these opportunities alone. Through consultation with experts, we defined three recommendations for further work to stimulate cross-industry collaboration on this topic:

1. Validate findings with organisations across the supply chain to ensure that we achieve support from all required stakeholders.
2. Gain a baseline understanding of current relevant work to identify potential partners and define areas to focus on.
3. Initiate cross-industry knowledge sharing and networking to define specific problem statements that are common across multiple industries.

We are now seeking input from businesses operating across the supply chain, independent and government funded research and technology organisations and experts in academia to continue developing the opportunities for collaboration identified from this initial piece of work.

If you are interested in being involved, please contact:

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Synergy Programme Manager, Royal Society of Chemistry
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9

Appendix

9.1 Research methodology

We engaged with a broad range of perspectives from academia and industry to understand the opportunities for collaboration in the area of non-metallic materials and corrosion. This section describes the consultation techniques used in this initial piece of work.

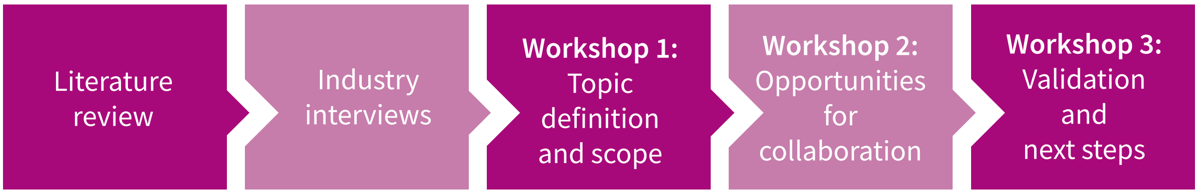

Figure 1:
Process for report

The first stage consisted of desk-based research, literature reviews and one-to-one interviews with practitioners from large companies to better define the topic. We invited four businesses from different industries to define the topic and scope in the first workshop.

We invited 22 experts from academia, industry, trade associations and catapults to the second workshop. This stage analysed external and business related factors affecting development over the 25-year timeframe and identified chemical science related challenges. Participants developed opportunities for collaboration to address these challenges and validated them in review and feedback sessions. In the final stage of the process, we held a third workshop with representatives from industry to further validate the opportunities defined in the second workshop and identify next steps required to generate action.

We used strategic roadmapping, a technique developed by the Institute for Manufacturing Department of Engineering at the University of Cambridge, throughout the process.[26] The output of this process is a series of roadmaps that define the current state and a plan to achieve a possible future state in a given timeframe. Industry often uses this technique to create a common approach between multiple stakeholders to address complex topics like sustainability. We used this technique because it is a widely tested approach, encourages collaboration and produces detailed and structured outputs. Strategic roadmapping also engages a wide stakeholder group, generates consensus for next steps and creates visual outputs to support communication.

9.2 Participating organisations

Airborne	Hexigone Inhibitors
AkzoNobel	Impact Solutions
Arup	Imperial College London
BAE systems	Johnson Matthey
Birmingham University	Lubrizol
British Aerosol Manufacturing Association	National Physical Laboratory
Centrica Storage	Qinetiq
CPI	TWI
EDF Energy	University of Hull
Eli Lilly	University of Manchester
Gnosys Global	Victrex

9.3 Data

Drivers and challenges	Opportunities: Open access database of reliable chemical data for selecting and applying non-metallic materials that can feed models that predict performance in different environments. This includes data on existing pre-failure points.	Standardised accelerated exposure tests for new materials in corrosive environments.	Modelling chemistry of materials and complex systems degradation and complex corrosive environments for predicting performance.	Standardised tests and characterisation methods, e.g. imaging to sense and understand integrity of materials for predicting life-time performance of non-metallic materials. Includes in situ/in operando.	Sustainable, scalable and high-performing replacements for fossil-derived materials, e.g. epoxy's including non-virgin and bio-sourced materials.	Techniques to manufacture materials from waste feedstocks and disassemble materials at the end of their life to recapture value and reuse, e.g. separation techniques, pyrolytic processing.
A greater emphasis on the circular economy is driving industry to look at alternative options but limited resources are available and cost of innovation is high						■
There is a lack of regulation and standards for materials characterisation and testing		■		■		
Environmental degradation of glass materials		■		■		
UN sustainability goals are influencing change					■	
We need to understand the exact composition and lifetime of polymers		■	■	■		
There is a lack of lifetime accelerated tests for metals and composites		■		■		
Characterising non-metallic materials is very costly		■		■		
Customers/end users already aspiring to change to reduce impact when considering materials and durability					■	
Safety legislation is prohibiting the use of materials (REACH)					■	
There is a need to monitor quality assurance of manufacturing processes						■
A move towards sustainable materials could preclude the use of certain materials in the future					■	
There is a need to develop products from recycled products					■	
Replacement of existing fossil fuel products requires extra bio based materials					■	
The carbon cost of today's corroding steel solutions may become unacceptable in the future					■	
Development of new materials will change how we design products					■	
We need to better understand/predict life-time performance of composites	■	■		■		
Through-life performance of long-life systems within structures		■		■		
Legislation will require existing materials like composite resins and fibres, and resins for paints to be more sustainable and be sourced from renewable sources					■	
We are uncertain whether customers want change or will pay for sustainability					■	
There is currently a lack of theoretical understanding to enable reliable lifetime prediction models which is limiting their application	■					
There is a need to extend lifetime service and performance so we need to better predict and model performance	■	■	■	■		
Non-metallic materials are less reliable to manufacture so there is a need to make manufacturing processes easier						■
Lifetime performance of non-metallic materials is not yet comparable with conventional materials, which may cause issues with durability and product shelf-lives	■					
There is a lack of engineering validation for non-metallic materials, especially in high-risk environments		■		■		
Various drivers pushing use of non-metallic materials, including lightweighting, but recycling and sustainability are issues					■	
The drive towards lightweighting is causing industry to use less metal so there is a need to prove corrosion mechanisms in non-metallics to find alternatives	■					
Materials will need to be designed with degradation processes in mind so that structures are durable throughout their lifetime and minimise extended presence in landfill						■

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About the Royal Society of Chemistry

We are an international organisation connecting chemical scientists with each other, with other scientists, and with society as a whole. Founded in 1841 and based in London, UK, we have an international membership of around 50,000. We use the surplus from our global publishing and knowledge business to give thousands of chemical scientists the support and resources required to make vital advances in chemical knowledge. We develop, recognise and celebrate professional capabilities, and we bring people together to spark new ideas and new partnerships. We support teachers to inspire future generations of scientists, and we speak up to influence the people making decisions that affect us all. We are a catalyst for the chemistry that enriches our world.

About Synergy

Synergy is the Royal Society of Chemistry's programme for industry, tackling complex chemistry topics through collaboration. We bring together businesses who face similar chemistry-related challenges and develop opportunities to solve them collaboratively. Through the programme, businesses can share knowledge with experts in different industries and sectors, reduce risks in research and development, and bring solutions to multiple markets faster.

In October 2019, 22 experts from across industry and academia came together for a workshop on the subject of corrosion. The aim was to explore how collaboration across chemistry could improve our understanding of the performance of non-metallic coatings and materials, enabling industries to develop their own solutions for their own markets.

Recommended readers

This report is for technical and non-technical experts operating in industries that manage corrosion, including:

- Industry and academic participants of the Synergy programme.
- Technical managers in relevant industries and supply chains.
- Academics working on corrosion, non-metallics and materials.
- Regulatory and standards bodies in the area of corrosion.
- Government organisations working in the area of sustainable corrosion management.

Stakeholders with decision-making capacity to drive collaborations that work to reduce the economic and environmental impact of corrosion may particularly find this report useful.

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