Inspired by nature: exploiting the beauty of biominerals

Nanomaterials expert and enthusiast **Dr Siddharth Patwardhan** provides an insight into the inner workings of his lab, and explains why his team's bioinspired research is so innovative

Why did you choose to pursue research in the field of bioinspired green nanomaterials? What fascinates you about this area of study?

Biology has mastered the art of producing sophisticated and ornate nanomaterials through a process called biomineralisation. Well-known examples include bones and teeth. The precision and beauty of biominerals is unique and admirable. Seeking inspiration from biominerals and learning how biology orchestrates the formation of such high-quality nanomaterials is fascinating, as is discovering the formation mechanisms and utilising them to develop new technologies. The potential impact of bioinspired technologies is huge, especially given the opportunity to reduce environmental damage caused by current processes.

What have been the biggest advances made by scientists with regard to silica-based materials using bioinspired approaches? How do these correlate with your research?

There are four main areas wherein scientists have made the biggest advances pertaining to bioinspired silica. The first of these is the identification of biological mechanisms that control the formation of biominerals. These include cellular processes as well as the isolation of specific biomolecules responsible for biomineral formation. Secondly, there is the translation of these mechanisms into the non-biological synthesis (fully synthetic in the lab) of biominerals by gaining understanding at the molecular level. The third area is the utilisation of the underpinning molecular-level science in producing a wide variety of silicas with varying properties. Finally, there is the translation of this knowledge into developing applications and manufacturing technologies. My group has contributed significantly in the last three areas, while recently, we have focused more closely on the applications and manufacturing.

Nanomaterials are used across a range of applications, from sensors and coatings to hybrid materials, catalysis and drug delivery systems (DDS). In what ways have you applied knowledge of the latter in your studies, given the ability of silica to control drug loading and delivery?

Many nanomaterials have been investigated for use as DDS, and silica has been proposed as a promising candidate. Although, over the past 15 years, silica has been tested with various drugs (ranging from anti-inflammatory to antibiotics and anticancer drugs), there are currently no silica-based drug delivery systems on the market. We identified the problems with the existing silica technologies, which include laborious synthesis, the use of hazardous chemicals and harsh conditions (extremes of temperatures and pH). We then utilised our knowledge of bioinspired silica to overcome these issues and design novel DDS. One radically new approach we have taken is direct loading of drugs into silica when silica is produced, as opposed to loading drugs after the silica powder has been produced. This approach reduces the production steps, and hence also cost and waste.

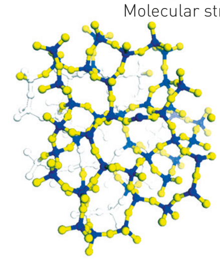
The industrial-scale design you proposed in your feasibility study is economically competitive, requires no heat and reduces carbon dioxide emissions in comparison to traditional methods. What further conclusions were you able to draw and how have you developed this research since?

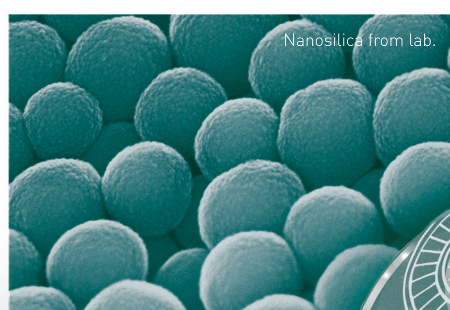
Since the publication of that feasibility (theoretical) study, we have put the outcomes into practice and we are now able to produce large amounts of silica (hundreds of grams to kilogram quantities compared to hundreds of milligrams, which anyone could produce beforehand). We have also developed greener ways for downstream processing (purification), which makes the entire process truly green and sustainable. These developments are under intellectual property protection and are at the commercialisation stages.

Why does the silica obtained via the bioinspired process result in a more diverse range of properties that can be controlled? What new applications could silica have?

Biology is able to offer superior control, hence bioinspired silica is also highly controllable and can be 'moulded' to generate a wide range of properties. We use specific molecules (called additives) that are inspired by biomolecules and help control the process. We have developed a vast amount of knowledge pertaining to the use of these additives in silica formation. We are constantly exploring new and exciting applications for bioinspired silica and recent avenues include treating waste water and capturing CO_2 from power plants (these are being developed in collaboration with other colleagues).

Molecular structure of silica.





Nanosilica from lab.

The significance of silica

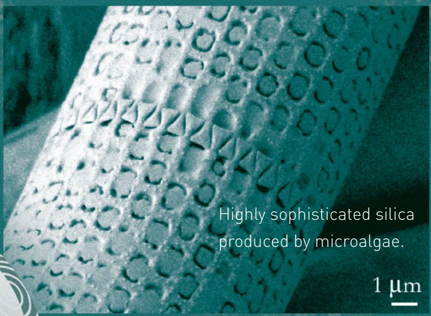
A system designed at the **University of Sheffield**, UK, could revolutionise the way nanoparticles are produced, with associated benefits for medicine

SINCE TIME IMMEMORIAL, humans have drawn inspiration from the natural world around them when attempting to overcome technological challenges. This process of biomimesis, the imitation of life, is evident in the works of Leonardo Da Vinci and the Wright brothers, ancient architecture, and even in everyday inventions like Velcro. And this is more than just a preoccupation with the organic; because of the refining effect that evolutionary processes can have, many of the forms observed in the natural world have close to optimal configurations to fulfil their various purposes. The curve of a sycamore leaf and the clinging pad of a gecko's foot may have arisen by chance – but they persist because they are effective.

One compound often found both in nature and in the lab is silicone dioxide, also known as silica. Silica is used in various applications – commonly in the packets of silica gel that reduce humidity in an environment, but also in synthetic products such as crystal and fused quartz. In nature, silica is an important component of many microalgae, plants and sponges; in the case of sponges, it often forms a delicate 'crystal' skeleton that supports the organism, and in plants too it can play a role in reinforcing the structure of the body. So strong of a scaffold is silica, that it gives strength to blades of grass – and, through these leaves, has influenced the evolution of grazing animals around the world.

DRUG DELIVERY

This begs the question: how effective could silicone dioxide be in human technology? Many scientists have worked towards answering this question. In particular, attempts have been made to use silica nanoparticles in drug delivery systems. Silica is an extremely attractive candidate for this application because its surface chemistry and porosity are easily controlled, its drug loading can be varied, it has been approved as safe in the EU and USA, and it has excellent biodegradation properties. It has even been suggested as a beneficial chemical for bone growth.



Highly sophisticated silica produced by microalgae.

But there are two problems: firstly, silica nanoparticles have to be synthesised under harsh conditions that are demanding in energy and not environmentally friendly. Secondly, questions remain regarding their toxicity and biocompatibility – scientists are not sure how cells react to them. Dr Siddharth Patwardhan is Senior Lecturer in the University of Sheffield's Department of Chemical and Biological Engineering and leader of the Green Nanomaterials Research Group. His aim is to solve these issues with the help of his dedicated team. Patwardhan's theory is that learning from nature, the synthesis of these nanoparticles may yield materials of greater use at a lower environmental cost.

THE LIVING END

Patwardhan's work centres on investigating living biosilicifying systems, which naturally operate at near-neutral pH, in aqueous environments and at ambient temperature, to see how they can inspire approaches to accomplishing the same in a lab. Towards this goal, 2011 saw the group publish a comprehensive and widely-read review of applications that had come out of this field of research, examining the potential for scaling up such measures in the future.

Much of the group's work has focused on the use of additives to enable and accelerate silica formation under diverse conditions – and, recently, the Sheffield scientists have been preparing for the publication of a very important study. The article will describe a new green process to facilitate rapid silica formation in less than five minutes and under ambient conditions. Their method, they say, is not only economically comparable to current industrial approaches, but also yields silica samples with superior properties to those created using other methods. By adopting this innovative green process, which can easily be incorporated in existing manufacturing without significant capital investment, industry will be able to create and adapt silica for current and new applications – a very exciting prospect indeed.

BIOINSPIRED GREEN NANOMATERIALS

OBJECTIVE

To discover, design and manufacture nanomaterials using sustainable processes for engineering, environmental and biomedical applications.

FUNDING

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DR SIDDHARTH PATWARDHAN obtained a first degree in Petrochemical Engineering from the University of Pune, India. This was followed by an MS and PhD in Materials Science and Engineering from the University of Cincinnati, USA. Subsequently, he gained postdoctoral experience from the University of Delaware and Nottingham Trent University. In 2010, Patwardhan became a lecturer in Chemical and Process Engineering at the University of Strathclyde. In 2016, he moved to the University of Sheffield to take up the position of Senior Lecturer in Chemical and Biological Engineering, where he leads the Green Nanomaterials Research Group. Patwardhan's research has produced 65 peer-reviewed articles, over 40 conference presentations and intellectual properties. Patwardhan is Associate Editor of *SILICON*, an elected member of the Royal Society of Chemistry's Materials Chemistry Division Council and EPSRC's Early Career Forum for Manufacturing Research. He has held visiting positions in Japan, India and the US. Patwardhan has also organised and served in scientific committees of national and international conferences.

The University Of Sheffield.