生物硅基功能性涂料光触媒对室内空气品质的改善（上）

Improving Indoor Air Quality Using a Biosilica-based Functional Paint & Coatings Photocatalyst (Part 1)

人类 90% 以上的时间是在室内度过的，然而室内环境中普遍存在着挥发性有机污染物（VOC）。地毯、涂料、木材染色剂、烟草烟雾、木材和塑料制品中的胶粘剂、电脑和电视机、常用家用化学清洁剂、霉菌以及大多数有香味和异味的物品都会散发出有机污染物。

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由于越来越推崇新型节能家居和建筑物，室内与外部环境的隔绝密封使室内空气质量问题更加的严重。因为挥发性有机化合物被限制在室内，这大大加剧了居住者吸入污染物的风险。Diatomix 公司开发了一种用于生物硅基光催化剂（已申请专利保护），该产品在添加到墙面涂料和地坪涂层中时可强力并持续地改善室内空气质量。通过去除挥发性有机污染物，该技术可以帮助抑制过敏和疾病造成的不适。本文展示了从实验测试到添加技术研发相关的成果。

背景

人类每天吸入大约 3,000 加仑的空气 [1]。因为人生 90% 的时间都处于室内环境 [2]，所以大部分情况都在室内吸入的。美国环境保护署指出，室内空气质量平均比室外空气质量差五倍 [1]。挥发性有机化合物（VOC）是造成室内空气质量下降的重要原因，其主要来源包括地毯、涂料、家具、木材染色剂、烟草烟雾、电脑和电视机、家用化学清洁剂和霉菌等 [3~4]。所产生挥发性有机化合物，如苯、甲基氯、甲醛等是致癌物质，并可能影响呼吸系统 [5~7]。挥发性有机化合物包括我们用来制造、装修和维护住房的许多产品中的多种化学物质。一旦这些化学物质进入室内，就会被释放或者挥发到我们呼吸的空气中，对呼吸者造成健康风险。有时，它们不会呈现可察觉的气味。在我们日常生活中，常见的挥发性有机污染物包括苯、乙二醇、甲醛、二氯甲烷、四氯乙烯、甲苯、二甲苯、1,3- 丁二烯等。

Individuals spend more than 90% of their lives in indoor environments. Volatile organic compounds (VOCs) are prevalent in indoor environments and are emitted from carpets, paints, wood stains, tobacco smoke, adhesives found in wood and plastic products, computers and TVs, typical household chemical cleaners, mold, and most scents and odours. Exacerbating this issue is the drive to make new energy efficient homes and buildings, which seals the indoor environments from the outside environment. This traps VOCs within the building, leading to greater inhalation risks to inhabitants. Diatomix Inc. has developed a patent pending, biosilica-based photocatalyst that actively and continuously improves indoor air quality when added to wall paint and floor coatings. By removing VOCs, the technology can help curb the discomfort associated with allergic symptoms and diseases. This paper presents findings from experimental work done to develop this filler technology.

Background

Humans breathe in around 3,000 gallons of air each day.[1] Most of that inhalation occurs indoors, where humans spend 90% of their time.[2] The Environmental Protection Agency of the US Government states that indoor air quality is, on average, 5 times worse than outdoor air quality.[1] Volatile organic compounds (VOCs) are major contributors to the degradation of indoor air-quality and primary sources include carpeting, paint, furniture, wood stains, tobacco smoke, computers and TVs, chemical cleaners and mold.[3~4] These sources produce VOCs such as benzene, methyl chloride, formaldehyde, and others that are carcinogenic and can affect the respiratory system.[5~7] VOCs are a large group of chemicals that are found in many products we use to build, furnish and maintain our homes. Once these chemicals are in our indoor structures, they are released or off-gassed into the indoor air we breathe and

室内的空气质量问题在包含高性能隔热层和隔汽层的经过改造的和新建的房中更加严重 [8]。近 20 年来，便携式空气淨化产品越来越受欢迎，因为它可以解决过敏原和空气中的微粒问题，但是大多数产品不能去除挥发性有机污染物 [9]。接触甲醛与儿童哮喘有很强的相关性 [10]，并且孕妇接触挥发性有机污染物会造成婴儿得湿疹的几率增加 [11]。美国约 6,000 万人受湿疹和哮喘的困扰，每年的治疗费用和所造成的经济损失超过 560 亿美元 [12~13]。短期接触挥发性有机污染物会造成头晕、刺激眼 / 鼻 / 咽喉和头痛，常年接触会导致癌症、损伤肝肾和破坏中枢神经系统 [14]。越来越多的研究表明室内空气污染与中风、缺血性心脏病、慢性阻塞性肺疾病、儿童呼吸道感染和肺癌相关 [15]。2012 年世界卫生组织 (The World Health Organization, WHO) 指出，全球多于八分之一的死亡是由接触污染空气造成的 [15]，这表明世界上环境健康最大威胁是空气污染。

室内空气污染的问题得到越来越广泛的报道和被人所识 [16~20]，使用便携式空气淨化器来改善室内空气质量也更加普及。但大多数淨化器只过滤颗粒物质，并不能去除挥发性有机化合物。另外，由于高成本和高能耗，这类设施并不被广泛使用 [21~23]。

由于全球城市化趋势和建筑施工的增加，建筑涂料市场继续增长。近年来，许多涂料公司致力于建筑涂料的创新，并引起社会对环保和功能性产品的关注 [24]。这形成了一个需求低挥发性有机污染物涂料的市场驱动因素。「绿色」已经成为涂料市场的主要新产品开发重点。绿色涂料毒性的更低，利于持续发展，占据 90 亿美元的全球涂料产值 [25]。绿色涂料正在成为环保涂层的重要一类。

随着越来越多的研究持续报道，环境压力不断加大，消费者对忽视室内空气质量造成的影响了解更多，对能减少挥发性有机化合物的功能性或「智能化」涂料的市场需求也将继续增长 [26]。一些公司推广主动吸附或光降解室内挥发性有机化合物的涂料添加剂技术。全球市场上有多种具有不同功能的产品。**表 1** 重点介绍了几个供应降低挥发性有机化合物涂料或填料技术的公司。Sto 公司 (德国 Stühlingen) 提供了一种应用光催化技术来解决室内空气质量问题的产品 (商品名 Climasan) [27~28]。他们推出了一种能中和怪味和降解污染物的室内涂料。可见光驱动的催化剂是他们的商业机密，涂料是基于聚丙烯酸酯的，但其固含量非常高。该公司不建议将产品用于卫生间和厨房等高湿环境中。位于菲律宾，马尼拉的 Boysen 涂料公司开发出了一种名为 KNOxOUT 空气清洁涂料的系列产品。KNOxOUT 的活性来 CrystalActiv，一种二氧化钛纳米粒子和碳酸钙填料。涂料中的二氧化钛是众所周知的能够降解各种有机分子的 UV 光驱动的催化剂。因为需要紫外线，这种涂料主要用于户外。Boysen 的目标是通过光催化将 NOx (一氧化氮 (NO) 和二氧化氮 (NO_2)) 氧化成毒性小很多的硝酸盐 (NO_3)。另外，陶氏化学公司 (美国密歇根州米德兰) 销售一种叫 Formashield的涂料，它含有可与醛类化合物反应的聚合物，能除掉室内空气中的醛类。这种涂料旨在从室内环境中去除甲醛，不能有效地处理室内大部分的挥发性有机污染物，因

pose health risks to those who breathe them. They may or may not present a perceptible odour. Common examples of VOCs that may be present in our daily lives are: benzene, ethylene glycol, formaldehyde, methylene chloride, tetrachloroethylene, toluene, xylene, 1,3-butadiene and many more.

Retrofits and new houses containing high-performance insulating layers and vapour barriers have exacerbated indoor air quality issues.[8] Portable air-purification products have grown in popularity over the past 20 years to address allergens and airborne particulates but most do not remove VOCs.[9] Exposure to formaldehyde has a strong correlation with childhood asthma[10] and maternal exposure to VOCs during in utero development has been correlated with increased eczema in children.[11] Eczema and asthma affect approximately 60 million people in the United States and cost the nation over $56 billion annually in treatment and lost economic opportunity.[12~13] Other symptoms of short-term exposure to VOCs can include dizziness, eye/nose/throat irritation, and headaches, while years of chronic exposure can cause cancer, liver and kidney damage, and central nervous system damage.[14] Increasing research underscores the connection between indoor air pollution and stroke, ischemic heart disease, chronic obstructive pulmonary disease, respiratory infections in children, and lung cancer.[15] The World Health Organization (WHO) reported in 2012 that more than one in eight global deaths was a result of air pollution exposure[15], which confirms that air pollution is now the world's largest single environmental health risk.

Indoor air pollution is becoming more widely reported and better understood,[16~20] and inhabitants more commonly use portable air-purifiers to improve indoor air quality. Most purifiers only address particulate matter and do not address VOC removal. Such units are not commonly utilised due to high cost and energy consumption.[21~23]

The architectural coatings market continues to grow due to increases in global urbanisation trends and construction activities. Over the years, many paint companies have been committed to innovations in architectural coatings and their efforts have led to societal awareness of eco-friendly products and products with functional benefits.[24] As a result, this has created a new market driver with increasing demand for low-VOC paints. "Green" products have become the dominant new product development focus of the paint and coatings market. Green coatings have lower toxicity and are more sustainable, comprising $9 billion of the global paint and coatings industry.[25] Green coatings are becoming an essential category of environmental protection coatings.

As more studies continue to be published, environmental pressures continue to mount, consumers become more educated about the impact of compromised indoor air quality, and the market demand for functional or "smart" coatings that reduce VOCs will continue to grow.[26] A number of companies sell additive technology for paint application which actively adsorb or photocatayltically degrade indoor air VOCs. There are a host of products on the market worldwide with a wide range of stated performance claims. **Table 1** highlights a few of these companies which currently provide VOC reducing paint or filler technology. Sto (Stühlingen, Germany) provides a product called Climasan that uses a photocatalytic technology to address indoor air quality. They released an odour-neutralising and pollutant degrading paint for interior applications. Their visual light catalyst is proprietary and although the paint is acrylic-based, it has a high percentage of solids. The company does not recommend the product for high-humidity environments such as bathrooms and kitchens. Boysen Paints (Manilla, Philippines) has developed a product line called KNOxOUT Air Cleaning Paint. The active technology in KNOxOUT is CrystalActiv, which is a titanium dioxide

表 1：Diatomix 的同类竞争产品列表
Table 1: Competitor products list versus Diatomix

	陶氏化学 Dow Chemical	Boysen 油漆 Boysen Paints	Sto 油漆 Sto Paints	Diatomix
产品 Product	FormaShield	Knoxout Paint	Climasan	TBD
总部 Headquarters	美国密歇根州米德兰 Midland, MI	菲律宾马尼拉 Manila, Philippines	德国 Stühlingen Stühlingen, Germany	美国俄勒冈州波特兰 Portland, OR
有效成分 Active ingredient(s)	特种聚合物 Specialty polymer	二氧化钛、碳酸钙 TiO_2, $CaCO_3$	视觉光催化剂 Visual light catalyst	装饰硅藻 Decorated diatoms
持续净化 Continuous decontamination	没有 No	有 Yes	有 Yes	有 Yes
零 VOC Zero-VOC	有 Yes	没有 No	有 Yes	有 Yes
光催化 Photocatalytic	没有 No	有 Yes	有 Yes	有 Yes
目标环境 Target environments	室内 Indoor	户外 Outdoor	室内 Indoor	室内 / 户外 Indoor/Outdoor
厨房和浴室可用 Kitchen & bathroom usable	有 Yes	没有 No	没有 No	有 Yes

为其只对醛类有活性。虽然 Formashield 不需要光就有活性，但随着时间的推移会吸附的污染物变得饱和并失去去除甲醛的能力。其活性持续的长短取决于室内空气中醛的浓度，环境条件越恶劣，越容易饱和及降低活性。美国俄亥俄州克利夫兰市宣威公司销售一种使用沸石添加剂吸附挥发性有机化合物的涂料，叫 Harmony。与 Formashield 类似，一旦饱和，就失去去消除挥发性有机污染物的能力；同样，在挥发性有机污染物含量越高的环境，涂料饱和的更快。

Diatomix 技术

Diatomix 开发出一种有助于减少室内挥发性有机污染物的特涂料添加剂技术（已申请专利）。通过结合高比表面积的硅藻土和二氧化钛，Diatomix 的光触媒技术实现了利用室内光源不断降解挥发性有机化合物（**图 1**）。二氧化钛是一种半导体，可以将多种美国环境保护署列为有害空气污染物的挥发性有机化合物矿化。Diatomix 用硅藻作为载体加强了二氧化钛的光催化作用。硅藻由二氧化硅组成，可吸附挥发性有机化合物，通过将光催化剂接近或接触挥发性有机化合物，可提高 VOC 降解的光电子转化效率。硅藻作为载体的最大优势是其纳米光捕获结构，对波长为 380~500 nm 的光，可提高 1.7 倍的吸能力。通过专有的沉积工艺优先将 TiO_2 附着在能富集光线的硅藻中；由于 VOC 吸附和光捕获的协同响应，其光催化效率更高。

总的来说，这项技术避免了在涂料中添加光催化活性二氧化钛的常见问题。将光催化活性二氧化钛加入涂料中造成的典型问题包括基料降解，低光电转化效率 (Incident-photon to Charge Conversion Efficiency, IPCE) 和催化剂的表面暴露问题 [29]。涂料基料的降解被涂料公司列为进入市场的主要障碍，因为 TiO_2 的光催化活性会氧化基料本身。较低的 IPCE 是二氧化钛光催化的一个普遍问题，导致污染物的降解速率对于大多数应用来说太慢。但是由于污染物浓度低，针对室内空气质量来说是一个好的选择 [29]。最后，使催化剂暴露在涂料的表面是必要的，但也比较困难，因为成膜基料会包覆催化剂颗粒。克服这些障碍是可能的，因为硅藻壳（藻类的玻璃骨架）具有高表面积的复杂结构，可以集中有用的光并能吸附挥发性有机污染物。我们专有的工艺使

nanoparticle and calcium carbonate filler. The titanium dioxide contained within the paint is a well-known UV photocatalyst that will degrade various organic molecules. The paint is only targeted at outdoor applications as it needs UV light. Boysen targets NOx (nitric oxide (NO) and nitrogen dioxide (NO_2)), which can be oxidised by photocatalysis to nitrate (NO_3), a much less toxic species. Dow Chemical (Midland, MI) sells Formashield, a paint with a specialty polymer that reacts with aldehydes, removing them from interior air. This paint is targeted at removing formaldehyde from interior environments. It is only active against aldehydes and cannot effectively treat the majority of VOCs found indoors. Formashield does not require light for activity but will become saturated over time and lose formaldehyde removal activity. How long it lasts depends on how concentrated the aldehydes are in indoor air making the worst environments the most susceptible to saturation and decreased activity. Sherwin-Williams (Cleveland, OH, USA) sells Harmony paint which uses zeolite additives to adsorb VOCs. Similar to Formashield, once saturated no more VOC removal will occur. In addition, higher VOC environments will saturate more quickly.

Diatomix technology

Diatomix has developed a patent pending and proprietary technology for a paint and coatings filler that helps reduce indoor air VOCs. By combining high-surface-area diatomaceous earth with titanium dioxide, Diatomix's photocatalyst technology uses indoor light sources to continuously degrade VOCs (**Figure 1**). Our TiO_2 is a semiconductor that has been shown to mineralise many VOCs cited by the EPA as hazardous air pollutants.[27~28] Diatomix's contribution to TiO_2 photocatalysis is the use of diatoms as our catalyst substrate. Diatoms are composed of SiO_2 and have been shown to adsorb VOCs, increasing the charge conversion efficiency of VOC degradation by placing the VOCs directly next to and even in contact with the catalyst. Diatoms' greatest strength as a substrate are the ability to act as nanophotonic light-trapping structures that can enhance absorption of light with wavelengths from 380 nm to 500 nm by 1.7 times. The proprietary coating process deposits TiO_2 preferentially inside the diatoms, where the light is concentrated. This combination of VOC adsorption and light trapping leads to improved photocatalytic efficiency.

The technology, by and large, has avoided the common pitfalls of adding photocatalytically active titanium dioxide to paint. The typical problems associated with adding photocatalytic TiO_2 into paint include binder degradation, low incident-photon to charge conversion efficiency (IPCE) and surface exposure of the catalyst.[29] Degrading the binder

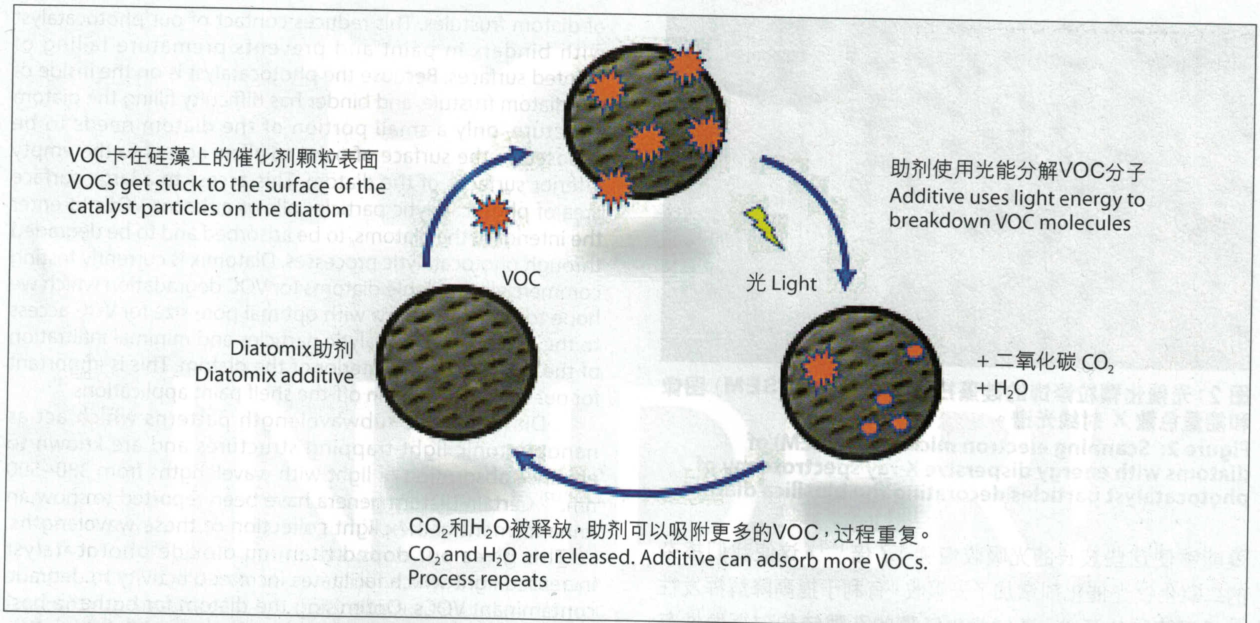

图 1：生物硅承载的催化剂颗粒捕获和连续降解挥发性有机污染物的机理。挥发性有机化合物和其它化合物完全转化为二氧化碳和水的过程被称为矿化。Diatomix 的添加剂可使挥发性有机污染物矿化，而其它去除挥发性有机污染物的添加剂没有这个功能。

Figure 1: Continuous degradation mechanism cycle of VOCs trapped by the biosilica decorated with catalyst particles. The complete conversion of VOCs and other compounds to CO_2 and water is termed mineralisation. The Diatomix additive can mineralise VOCs. This being the key differentiator between it and other VOC removing additives.

大部分二氧化钛沉积在硅藻壳内部（**图 2~3**）。Diatomix 生物硅的承载二氧化钛具高的表面积[30]，并且可吸附有机分子。如前所述，这有助于将挥发性有机污染物聚集在光催化剂附近。而且 Diatomix 创造了一种可扩展的制造工艺（已申请专利），能在硅藻壳表面融合 5~10 nm 的二氧化钛纳米颗粒。

如**图 2** 所示，合成的二氧化钛纳米粒子牢固地附着在生物硅表面；每个纳米粒子都与相邻粒子独立分离。通过监测挥发性有机污染物降解的副产品，我们发现光催化剂修饰的硅藻壳在光存在的情况下能够连续快速捕获并将挥发性有机污染物转化成为水和二氧化碳。

通过 Diatomix 专有的合成方法，结合使用低分子量有机钛前驱体的化学气相沉积和火焰热解，二氧化钛光催化剂优先沉积在硅藻内外的细微骨架上。由于硅藻的内表面具有高比表面积（**图 2~3**）和精细结构，二氧化钛集中在硅藻壳的细孔里和内部结构。这减少了光触媒与涂料基料的接触，并防止涂料表面的过早失效。由于光催化剂位于硅藻壳内部，基料难以填充硅藻内部，所以只需要一小部分硅藻曝露于涂料表面，使空气和挥发性有机污染物到达硅藻的内部。空气中的挥发性有机化合物可以进入硅藻内部，通过与光触媒颗粒的大面积接触，被吸附和光催化降解。Diatomix 目前正在测试市场上销售的硅藻对光催化降解挥发性有机污染物的增强作用，我们希望通过这种方式，可以发现具有最佳孔隙尺寸的硅藻，既能使挥发性有机污染物接触到内部的光催化颗粒，又能避免基料渗入到硅藻内。这对于能不能在现成的涂料应用我们的添加剂是非常重要的[31]。

硅藻近于光波长的孔隙阵列是一种纳米光捕获结构，可增强 380~500 nm 波长的光的吸收[32]。据报道，某些硅

in paint has been cited by paint companies as a major hurdle to market entry and is due to the photocatalytic activity of TiO_2 oxidising the binder itself. Low IPCE is a general problem for TiO_2 photocatalysis and causes the degradation rate of pollutants to be too slow for most applications but indoor air quality has been cited as a good target because of the low concentration of pollutants.[29] Lastly, surface exposure of the catalyst from paint is necessary but also challenging as the binder will coat the catalytic particles. Overcoming these obstacles is possible because diatom frustules (the glass skeletons of algae) have intricate interior surface structures with high surface area, concentrate the useful wavelengths of light and are known to adsorb VOCs. The majority of TiO_2 is deposited, through our proprietary process, on the inside of the diatom frustule (**Figures 2~3**). Diatomix TiO_2 coating of biosilica cell walls have high surface areas and are known to adsorb organic molecules.[30] As mentioned earlier, this helps assist the catalyst by placing the VOCs directly next to the photocatalysts. Diatomix has created a scalable manufacturing process (patent-pending) to fuse 5~10 nm TiO_2 nanoparticles on the surfaces of diatom frustules.

As shown in **Figure 2**, as-synthesised TiO_2 nanoparticles firmly anchor on biosilica surfaces; each nanoparticle is discretely separated from its neighbors. By monitoring the byproduct of the degraded model VOCs, we found that photocatalyst-decorated diatom frustules rapidly trap and chemically convert VOCs to water and carbon dioxide on a continuous basis, in the presence of light.

Through Diatomix's proprietary synthesis method, combining chemical vapour deposition and flame pyrolysis using low molecular weight organic titanium precursors, the titanium dioxide photocatalyst is preferentially deposited onto the smallest physical structures of the diatoms' interior and exterior surfaces. Since the interior surface of diatoms has high surface area (**Figures 2~3**) and fine substructures the titanium dioxide is concentrated in the pores and on the inside

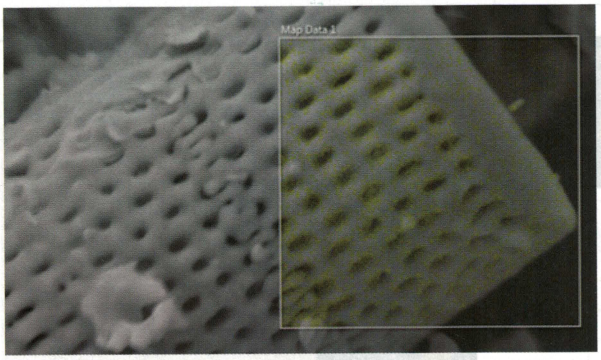

图 2：光催化颗粒修饰的硅藻扫描电子显微镜（SEM）图像和能量色散 X 射线光谱。

Figure 2: Scanning electron microscopy (SEM) of diatoms with energy dispersive X-ray spectroscopy of photocatalyst particles decorating the biosilica diatom.

藻能够使这些波长的光吸收增强 1.7 倍 [32]。这使我们掺杂的二氧化钛光催化剂增加了光吸收，有利于提高降解挥发性有机污染物的活性。通过优化硅藻的孔隙结构对挥发性有机污染物流通的影响，表面曝露和光诱导增强，我们将成功实现涂料的光触媒功能。

挥发性有机化合物和其它化合物完全转化为二氧化碳和水被称为矿化。我们的系统显示 VOC 的矿化是重要的，因为这是我们的产品和其它去除 VOC 的涂料添加剂之间的主要区别。Diatomix 已经显示了良好的降解速率，当用普通的 23 瓦白色荧光灯照射时每克 Diatomix 技术产品，大约可将 1 毫克 / 小时•立方米 VOC（测定甲醇为 3 毫克 / 小时•立方米，二氯甲烷 0.6 毫克 / 小时•立方米）降解为二氧化碳。平均 1 平方米的墙面涂装加入 10% 我们技术的涂料将有大约 30 克的硅藻。理论上，平均涂层厚度为 100 微米，我们的硅藻为 10 微米，干燥后应至少有 2% 的硅藻曝露在表面。这意味着在一个平均 9 x 9 米的房间里，墙壁上会有大约 1,000 克的添加剂。如果只有 1% 的催化剂表面曝露（而不是理论值的 2%），我们预期挥发性有机化合物如甲醛的去除率应该高达 10 毫克 / 平方米•小时，达到 LEED 空气质量信用所要求的 20 倍的浓度水平 [34]。房屋内 VOC 总量的平均浓度变化很大，但由于 VOC 含量较高时我们的技术将运行得更快，可能会缓解高 VOC 的情况 [35]。

of diatom frustules. This reduces contact of our photocatalyst with binders in paint and prevents premature failing of painted surfaces. Because the photocatalyst is on the inside of the diatom frustule, and binder has difficulty filling the diatom structure, only a small portion of the diatom needs to be exposed to the surface of paint to allow access to the empty interior surfaces of the diatom. This access to a large surface area of photocatalytic particles allows airborne VOCs to enter the interior of the diatoms, to be adsorbed and to be degraded through photocatalytic processes. Diatomix is currently testing commercially available diatoms for VOC degradation which we hope to lead to diatoms with optimal pore size for VOC access to the interior photocatalytic particles and minimal infiltration of the binder into the interior of the diatom. This is important for our system to work in off-the shelf paint applications.[31]

Diatoms have subwavelength patterns which act as nanophotonic light-trapping structures and are known to enhance absorption of light with wavelengths from 380~500 nm.[32] Certain diatom genera have been reported to show an enhancement of 1.7x light collection of these wavelengths.[32] This gives our doped titanium dioxide photocatalyst increased light which facilitates increased activity to degrade contaminant VOCs. Optimising the diatom for both the best pore size for VOC access, surface exposure and light trapping enhancement will give our photocatalyst the best opportunity to succeed as a functional coating.

The complete conversion of VOCs and other compounds to CO_2 and water is termed mineralisation. It is important for our system to show mineralisation of VOCs as this is the key differentiator between our product and other VOC removing paint additives. Diatomix has seen good degradation rates, around 1 mg VOC$*h^{-1}*m^{-3}$ per gram of Diatomix technology (determined from methanol, 3 mg$*h^{-1}*m^{-3}$ per gram, and dichloromethane, 0.6 mg$*h^{-1}*m^{-3}$ per gram) to CO_2, when irradiated with common 23 W white fluorescent bulbs. On average 1 m^2 of wall covered with paint with 10% of our technology added will have approximately 30 g of diatoms. Theoretically with the average paint layer being 100 µm thick and our diatom at 10 µm, 2% of the diatoms should have at least some portion exposed to the surface based on volume after drying. This means that an average 9 x 9 m room would have around 1000 g of additive in the walls. If only 1% of the catalyst surface is exposed (instead of the theoretical 2%) we should expect up to 10 mg$*m^{-2}*h^{-1}$ removal rate of a VOC such as formaldehyde, 20 times the concentration level needed to achieve LEED air quality credits.[34] The average concentration of total VOCs in houses varies significantly, but since our technology will work faster with more VOCs present, mitigation of high VOC situations is likely.[35]

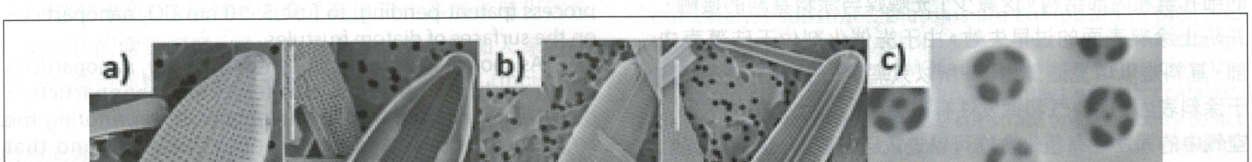

图 3：硅藻外部（a 及 b 左方），内部（a 及 b 右方）[33] 和内部孔（c）的图示

Figure 3: Exterior (a & b left) and interior (a & b right) views of diatoms.[33] c) Interior pore view