Institution: Swansea University		
Unit of Assessment: 12		
Title of case study: The commercial, production and environmental benefits of improved membrane design for industry and healthcare.		
Period when the underpinning research was undertaken: 2005 - 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Chris J. Wright Nidal Hilal	**Role(s) (e.g. job title):** Reader Professor	**Period(s) employed by submitting HEI:** 1996-present 1998-2001; 2010-30th August 2020
Period when the claimed impact occurred: 2014 - 2019		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

The industrial application of synthetic membranes in separation processes is rapidly expanding. Research at Swansea University, sustained over multiple REF periods (between 2005 and 2020), has contributed significantly to the positive commercial, production and environmental impacts of membrane systems. We have developed new membrane separation processes that have created long-term operating expense savings in healthcare and food industries. The benefits of our research between 2014 and 2020 includes the following:

- Commercial impact - optimisation of membrane systems enabling GBP1,000,000 in sales to membrane manufacturer Axium.
- Environmental and commercial impacts - improved whey processing for UK Dairy company First Milk, providing energy savings of over GBP3,500,000.
- Commercial impact - establishment of commercial electrospinning, a membrane manufacturing technique, for Hybrisan, which resulted in private investment, new products, sales and new job creation, contributing over GBP1,000,000 to the economy.
- Commercial and production impact - formation of a spin-out company ProColl, to exploit the novel membrane extraction of collagens at scale securing private investment of GBP450,000 and contracted sales over GBP3,000,000.

2. Underpinning research

Industrial process engineering

Membrane separation processes that remove water and raw materials from aqueous systems play an essential role to the operation of various industries. Synthetic membranes are used extensively for these separation processes to separate or concentrate materials from process streams based on particle/pore size and charge differences of the membrane. However, these membrane separation processes are energy demanding, and in fact are responsible for 7% of all energy consumed globally (AICheE Journal, 2012, 58). The advantage of reducing energy consumption has meant that membrane systems play a crucial role in meeting the 21st century challenges of membrane separation processes for environmental sustainability.

Prof Hilal and Dr Wright's research on optimisation of membrane systems by development of new membrane separation processes and the modification of membrane materials to improve process performance is key to their continued success in applications **[R1-R4] [P1-P8]**. Swansea University's optimisation procedures are based on stringent theoretical frameworks focussing on '*ab initio*' methods that were first developed at Swansea **[R1]**. This is supported by state-of-the-art characterisation techniques that we pioneered for membrane research, such as atomic force microscopy (AFM) and its capability to directly measure surface interactions forces, which govern how particles and surfaces in a process stream behave during separation **[R2]**. By understanding such forces and how they can be altered to improve membrane separation process performance, the polymer content of synthetic membranes can be optimised. Thus, this optimisation has also been supported by a comprehensive polymer membrane fabrication and modification strategy, such as coating membrane surfaces with antimicrobial nanoparticles, or creating membranes with nanofibrous structures using electrospinning **[R6]**.

Membranes have a key process advantage in that they operate at lower temperatures and pressures compared with other separation techniques for water treatment (such as evaporation). Our optimisation research has allowed for reduced energy needs by improving the design of many membrane systems, through either novel modification of the polymer membrane or process plant **[R1-R5], [G1] & [P1, P8]**. For example, we optimised the combination of membrane separation processes in a hybrid ion exchange-nanofiltration system for desalinating feed water to improve consistency in terms of salt and contaminant concentration.

Healthcare

In healthcare, membranes can be used as dressings or tissue engineering scaffolds, or to separate high value molecules, such as collagen or drugs. Healthcare advances in electrospinning have led to it being economically viable for high-throughput manufacture of membrane materials. We have developed techniques for the electrospinning of novel membranes for air gap membrane distillation and antimicrobial treatment at scale **[R4, R6], [G2]**. The latter demonstrates the reach of the research, as new methods for controlling biofilms are increasingly being recognised as essential due to antibiotic-resistant strains becoming predominant.

A novel application of membranes that we have been developing since 2015, and which has benefitted from our optimisation procedures, is the extraction of collagen from a range of animal sources at previously unobtainable levels **[P2]**. This research was funded by Research Councils UK (RCUK) **[G3, G4]** and by a Royal Academy of Engineering (RAEng) Entrepreneurial Fellowship **[G5]**. Membranes had not previously been applied for the extraction of collagen as the process conditions were believed to denature the protein.

3. References to the research

The outputs below all appear in Q1 (JCR) peer-reviewed journals. Two papers are written with international collaborators and three acknowledge external funding (e.g. EPSRC). The body of work is supported by competitively won grants totalling GBP1,260,035. This research has made important contributions to the discipline internationally and contributes important knowledge to the field likely to have a lasting influence.

[R1] Ahmed, F., Hashaikeh, R., Diabat, A., & **Hilal, N**. (2019). Mathematical and optimization modelling in desalination: State-of-the-art and future direction. *Desalination*, 469, 114092. doi.org/10.1016/j.desal.2019.114092

[R2] Powell, L., **Hilal, N.**, & **Wright, C.J.** (2017). Atomic force microscopy study of the biofouling and mechanical properties of virgin and industrially fouled reverse osmosis membranes. *Desalination*, 404, 313-321. doi.org/10.1016/j.desal.2016.11.010

[R3] Hilal, N., Kochkodan, V., Al Abdulgader, H., Mandale, S., & Al-Jlil, S. (2015). A combined ion exchange–nanofiltration process for water desalination: III. Pilot scale studies. *Desalination*, 363, 58-63. doi.org/10.1016/j.desal.2014.11.030

[R4] Cheng, S., Williams, P.M., Oatley, D., & **Wright, C.J.** (2011). Positively charged nanofiltration membranes: Review of current fabrication methods and introduction of a novel approach. *Advances in Colloid and Interface Science*, 164 (1-2), 12-20. doi.org/10.1016/j.cis.2010.12.010

[R5] Cheng, S.Y., Oatley, D.L., Williams, P.M., & **Wright, C.J.** (2012). Characterisation and application of a novel positively charged nanofiltration membrane for the treatment of textile industry wastewaters. *Water Research*, 46 (1), 33-42. doi.org/10.1016/j.watres.2011.10.011

[R6] Burke, L., Mortimer, C.J., Curtis, D.J., Lewis, A.R., Williams, R., Hawkins, K., Maffeis, T.G.G., & **Wright, C.J.** (2017). In-situ synthesis of magnetic iron-oxide nanoparticle-nanofibre composites using electrospinning. *Materials Science and Engineering C*, 70 (1), 512-519. doi.org/10.1016/j.msec.2016.09.014

Grants

[G1] Hilal, N., & Mohammad, A.W., [Principal Investigators]. (2017-2022). Towards water sustainability in the Malaysian agriculture industry: Water reclamation and nutrient recovery from palm oil mill biogas reactor effluent using an integrated forward osmosis process. [IC160133]. Royal Society. GBP307,680.
[G2] Wright, C.J., White, J.O., Claypole, T.C., & Gethin, D.T. [Co-Investigators]. (2010-2014). Ambulatory Magneto-Enhancement of Transdermal High Yield Silver Therapy (AMETHYST). [231986]. FP7, European Commission. GBP1,500,000 Total; GBP425,165 Swansea.
[G3] Williams, P.R., **Wright, C.J.**, & Hawkins, K., [Co-Investigators]. (2010-2014). Probing the Mechanical Control of Stem Cell Fate through the Development of Novel, Non-invasive Imaging Technologies. [EP/H045848/1]. EPSRC. GBP1,500,000 Total; GBP437,000 Swansea.
[G4] Wright, C.J. [Principal Investigator]. (2018-2019). Commercialisation Of Procoll Ltd'S Single Alpha Chain Collagen Derived. Commercialisation of Collagen Research. [15-21/ 518470155]. Innovate UK. GBP30,190.
[G5] Wright, C.J., & Widdowson, J. [Principal Investigators]. (2019-2020). Entrepreneurial Fellowship - Commercialisation Of Single Alpha Chain Collagen Technologies. [EF1819\8\74]. Royal Academy of Engineering. GBP60,000.

Patents
[P1] Hilal, N. (2013). Treatment of Produced Water. [Application number GB 1300406]. (filed by Swansea University in UK)
[P2] Widdowson, J., & **Wright, C.** (2018). Monomeric Collagen. [6067P]. (filed by Swansea University)
[P3] Hashaikeh, R., Lalia, B., & **Hilal, N.** (2014). Novel In-Situ Membrane Cleaning. [Application number for the USPTO utility 14/169,764]. (filed by Masdar Institute of Science and Technology, USA)
[P4] Atieh, M. A., Rhadfi, T., Fard, A.K., Khraisheh, M.K., & **Hilal, N.** (2016). MXene as New Adsorbent for Heavy Metals. [QF number: D 2015-0019]. (filed by Qatar Foundation (QF), USA)
[P5] Atieh, M.A., Rhadfi, T., Fard, A.K., Khraisheh, M.K., & **Hilal, N.** (2015). Removal of Barium with 2D Carbon Nano-Material from Natural and Produced/Co-Produced Waters. [QF number: D2015-0020]. (filed by QF, USA)
[P6] Atieh, M.A., Rhadfi, T., Fard, A.K., Khraisheh, M.K., & **Hilal, N.** (2015). Total Removal of Strontium from Water using Doped Activated Carbon (DAC). [QF number: D2015-042]. (filed by QF, USA)
[P7] Fard, A.K., Rhadfi, T., Atieh, M.A., Khraisheh, M.K., & **Hilal, N.** (2017). Total Removal of Oil from Water using Doped Carbon Nanotube (CNT). [QF number: D2015-059]. (filed by QF, USA)
[P8] Liu, Z., Wang, K., Saththasivam, J., El-Masri, D., & **Hilal, N.** (2018). A New Membrane for Oil/Water Separation. [PCT/QA2017/050002]. (filed by QF, USA)

4. Details of the impact

Swansea University research has focussed on the application of novel membranes to optimise water treatment processes, thereby making it more attractive than other methods, such as evaporation, and applied it to the food and biomaterial industries. The validity of this research for membrane separation process optimisation has been maintained throughout the REF2021 period by initiating significant active industrial engagement. This has ensured that our research is available to the relevant industries. Below, we provide examples of economic, commercial, production and environmental impact in the process industries for water treatment, food and regenerative medicine.

Membrane use in industry

Improved design of membrane systems [R1-5]
Axium Process is a Welsh Small to Medium-sized Enterprise (SME) employing over 50 people and is a major international player in the field of membrane and filtration technologies. It is one of the UK's leading stainless-steel fabricators specialising in hygienic engineering design, fabrication

and system solutions. Axium Process built and deployed membrane systems for water treatment, based on our optimisation research as summarised in **[R1],** which contributed GBP1,000,000 to the company while generating highly paid and skilled employment opportunities for local manufacturing companies.

In the letter of support Axium Process state:

"In economic terms the work conducted at Swansea University contributed in excess of £1M to the economy while simultaneously generating highly paid and skilled employment opportunities for local manufacturing companies." Business Development Director, Axium Process Ltd **[C1]**.

Improved food processing [R1-5].
First Milk (a British farmer-owned dairy co-operative) have seen the continuous impact of our research **[R4]**. Using Swansea research, they adapted their process and replaced evaporators with nanofiltration membrane technology and invested in new whey processing equipment leading to energy savings and related environmental impact. First Milk state:

"…during the period of the research exercise impact assessment window 1st August 2013 to present the membrane research of the College of Engineering has provided over £3.5 million of energy savings to First Milk." Site Manager, First Milk Cheese Co Ltd **[C2]**.

These process improvements have economic impact for First Milk and have improved the sustainability of the company by reducing the carbon footprint of their operations.

Membrane use for medical applications

Improved antimicrobial materials [R6].
Hybrisan is a Swansea based company specialising in the fabrication and scale-up of membrane manufacturing processes, particularly for electrospinning, which they exploit to prevent and control microbial and viral contamination. Hybrisan have used our membrane research **[R6]** in the development of membranes with fibres of different sizes and containing antimicrobials in products for aerospace filters and wound dressings. In 2020, they secured external investment from the Development Bank of Wales to achieve this using Swansea University research to enable scale-up of manufacture. Hybrisan state:

"The research of the Biomaterials, Biofouling and Biofilms Engineering Laboratory (B3EL) [Swansea University] *on the fabrication and optimisation of membranes alongside its work on biofouling has contributed towards exciting new business opportunities for Hybrisan in terms of new products and sales. In economic terms the research has assisted the company in the generation of in excess £1M to the economy through the creation of 5 new jobs for highly skilled individuals, investment by the company in business opportunities and sales of our products."* Technical Director, Hybrisan Ltd **[C3]**.

Application of membrane optimisation for improved production of collagen [R1-5].
The global collagen market was estimated at USD3,710,000,000 in 2016 and is expected to witness substantial growth by 2025 to USD7,500,000,000, mainly as a result of the growing demand for collagen from key industries including food & beverage, cosmetics, and healthcare. Thus, the impact we have had within this area has substantial depth and reach. Between 2015 and 2018 we extended our membrane optimisation research by developing a new membrane separation process for the extraction of collagens **[P2]**. The impact of Swansea research allowed ProColl, a spinout company formed in 2018, to increase manufacture from gram (g) to kilogram (kg) scale which was previously unachievable for the types of collagens that are key biomaterials in regenerative medicine and nutraceuticals. This is now being commercially exploited by ProColl. This demonstrates the substantial growth of the spin-out company and is a direct impact of Swansea University research. ProColl state:

"The success of our company has been enabled by adopting the processes that have been developed during the excellent research of the College of Engineering Swansea, we are now able to manufacture novel collagens at scale, this has led to investment, sales and the creation of 4 jobs. The research of the College of Engineering has significantly contributed to ProColl attracting funding and investment totalling £450K, with ongoing service contracts worth over £3M." CEO, ProColl Ltd **[C4].**

5. Sources to corroborate the impact

Where organisations provide testimonials below, in what capacity they are involved with the impact follows in brackets:

[C1] Letter of support: Business Development Director, Axium Process Ltd (Reporter)
[C2] Letter of support: Site Manager, First Milk Cheese Co Ltd (Reporter)
[C3] Letter of support: Technical Director, Hybrisan Ltd (Reporter)
[C4] Letter of support: CEO, ProColl Ltd (Reporter)