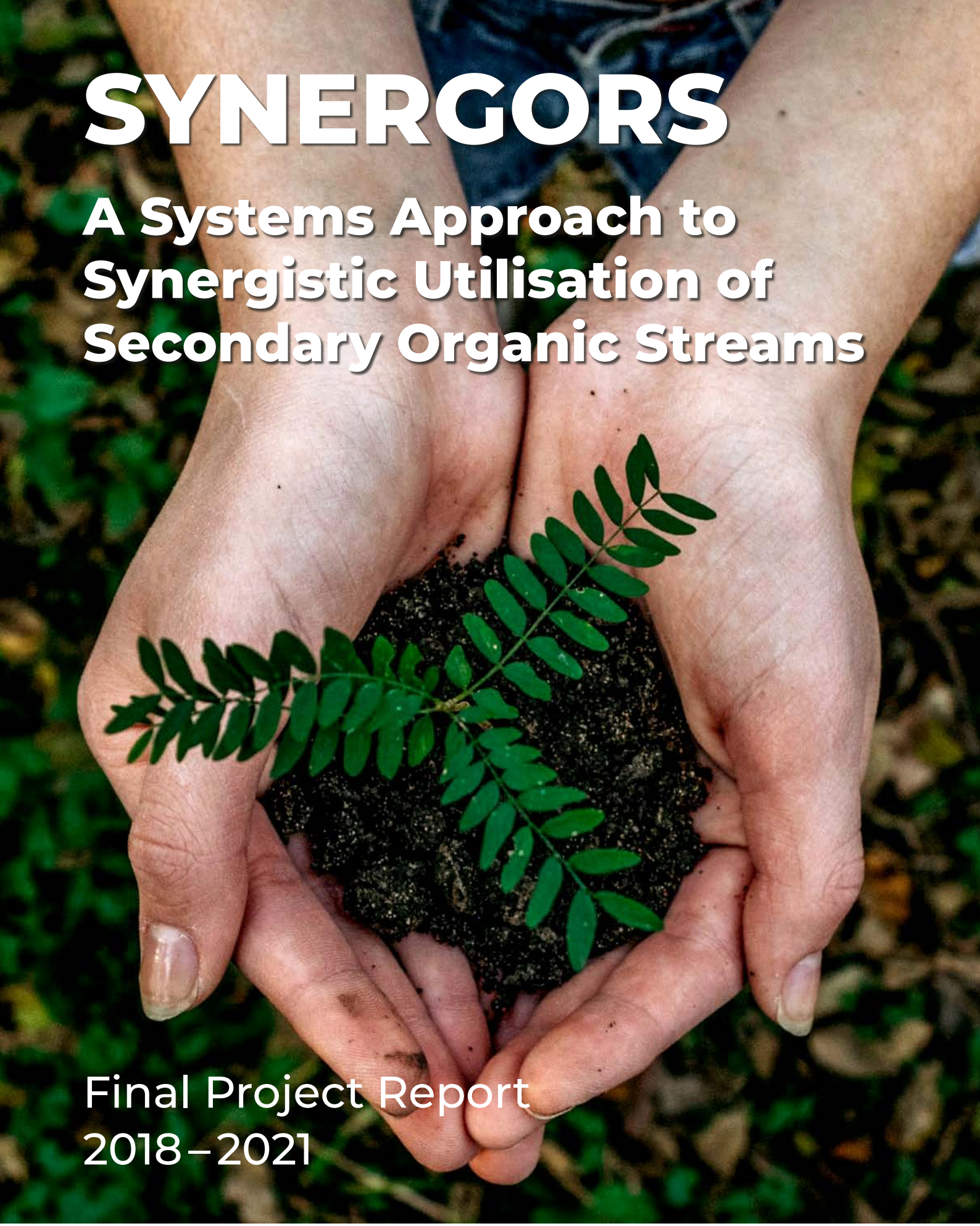

SYNERGORS

A Systems Approach to Synergistic Utilisation of Secondary Organic Streams

Final Project Report
2018–2021

Synergors

UKRI Natural Environment Research Council

Department of Engineering Science

University of Oxford

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SYNERGORS Final Project Report

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Foreword

The current linear "take-make-dispose" economy has resulted in excessive use of resources, and current strategies which mainly target pollution prevention and waste treatment do not fundamentally improve resource efficiency. We need to undertake a holistic and unified approach, in view of achieving a more circular economy and making progress towards net zero targets. This can only be realised through a systems approach; accelerating the uptake of transformative technologies in the industry; and policy harmonisation. Taking a holistic approach in tackling the climate change and resources and waste management challenges would prevent risk and problem shifting from one end to another. As Albert Einstein said, "we cannot solve our problems with the same thinking we used when we created them". Thus, we need to integrate our knowledge and expertise from various disciplines and sectors and solve the problems together at a global scale.

The SYNERGORS project ("*A systems approach to synergistic utilisation of secondary organic streams*"), funded by UKRI/NERC aims to develop novel systems approaches for promoting resource recovery from secondary organic waste streams including food waste, residual biomass and municipal solid waste. SYNERGORS has striven to provide significant insights into various options for organic waste recovery and valorisation through innovative technological design concepts and rigorous strategic analysis incorporating technical, economic, environmental and social assessments. The project has received support from more than 10 UK and international academic and industrial partners, providing multidisciplinary expertise to address the global challenges in resources and waste management. The outcomes from this project can be adopted in the UK and other countries to improve their policies, technologies and practices in relation to organic waste management. The objectives of the project are well aligned with the UK Industrial Strategy in enhancing resource efficiency while achieving a sustainable industrial growth and a more resilient economy.

One of the major impacts from this project is the creation of a new international Society of Circular, Regenerative and Sustainable Systems (CRES) which was officially launched at University of Oxford on the 3rd February 2020. CRES is built upon the UK and international networks developed through the SYNERGORS consortium and serves as a knowledge exchange platform to promote systems thinking and circular economy through a collaborative approach, bringing together academia, industry, government and society in order to integrate systems thinking into decision-making.

I gratefully acknowledge my funder UKRI/NERC for their generous support on this project; University of Oxford for hosting and supporting the implementation of this project; my collaborators and colleagues for their enormous contributions to this project.

Dr Kok Siew Ng
Principal Investigator of SYNERGORS
President of CRES

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Executive Summary

The SYNERGORS project ("A systems approach to synergistic utilisation of secondary organic streams") was funded by the UKRI Natural Environment Research Council (NERC), running from 2018 to 2021. The project aimed to develop new systems approaches for promoting resource recovery from secondary organic waste streams including food waste, residual biomass and municipal solid waste. The project received support from more than 10 UK and international organisations, including academia, industry and policymakers, to provide multidisciplinary expertise to address the global challenges in resources and waste management. The formation of the core team was greatly assisted by the British Council / Newton Fund Researcher Links workshops, with collaboration between the British, Malaysian, Mexican and Brazilian academics.

The SYNERGORS project has led to substantial impacts beyond academia, resulting in 9 academic publications, new experimental studies with Anaero Technology, a number of engagement activities and international visits (including case studies in Malaysia, Brazil and Mexico), and the creation of the Society of Circular, Regenerative and Sustainable Systems (CRES) which aims to promote systems thinking and circular economy.

SYNERGORS's research spans three themes:

Theme 1: Strategic analysis for sustainable organic resources and waste management to achieve circular economy and net zero

Theme 2: Development of novel resource recovery and valorisation technology concept

Theme 3: Development of innovative biorefinery system design

Key Recommendations from SYNERGORS

1. Waste and recycling industries should move away from a treatment-oriented waste management approach and adopt a more transformative and innovative resource recovery approach to achieve a more circular economy.

2. A systems approach to addressing waste management is needed to promote collaboration among different groups of stakeholders (e.g. government, local authorities, waste and recycling industries, commercial sector, public etc.)

3. Resources embedded in organic waste streams should be exploited for value-added products such as chemicals and hydrogen. This requires significant revamp on existing waste treatment facilities. Further research is needed to improve system efficiency and achieve greater cost reduction.

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1. SYNERGORS Project and Team Formation

SYNERGORS's research focus was inspired by two key characteristics of sustainable development: (a) the importance of multidisciplinary collaboration; and (b) the importance of a systems approach. The Core Team was then formed, following support of the project from the Natural Environment Research Council and with links developed through the British Council/Newton Fund Researcher Links workshops in Malaysia, Mexico and Brazil. SYNERGORS's research is well aligned with the focus of the Systems Engineering group (Chemical Engineering) in the Department of Engineering Science, University of Oxford.

The importance of multidisciplinary collaboration

The importance of multidisciplinary collaboration was made clear to Dr Kok Siew Ng, the Principal Investigator for the SYNERGORS project, during his experience in the Centre for Environment and Sustainability (CES) at the University of Surrey during 2015-2017.

During this time, Dr Kok Siew Ng worked on the MeteoRR project ("Microbial Electrochemical Technology for Resource Recovery", which aimed to achieve efficient resource recovery from wastewater using microbial electrochemical technology) within the Natural Environment Research Council's Resource Recovery from Waste (RRfW) Programme. This is a collaborative research programme aiming to develop knowledge and tools to reduce pressure on natural resources and create value from wastes. During his time on the RRfW Programme, Dr Kok Siew Ng had the opportunity to work with researchers from across different disciplines and organisations, including Newcastle University, the Universities of Manchester and South Wales, as well as Chivas Brothers and Tata Steel. Dr Kok Siew Ng also contributed to two mini projects in collaboration with Dr Eleni Iacovidou and Dr Anne Velenturf at the University of Leeds – *"Formulating the Environmental and Social Business Case for a Resource Recovery from Waste Process"* and *"Recovering Multidimensional Value from Compost Oversize"*.

The importance of a systems approach

In an engineered systems context, a systems approach is a holistic and multidisciplinary approach that examines the whole system, lifecycle and stakeholder community and ensures that the purpose of the system is achieved sustainably without causing any negative unintended consequences. This approach was inspired by the Natural Environment Research Council's project in Surrey *"Sustainability Assessment of Bioelectrochemical Systems"*, as well as the approach of the Centre for Environment and Sustainability (CES) at the University of Surrey and the Systems Engineering group (Chemical Engineering) at the University of Oxford.

Creation of Core Team: striving for international collaboration

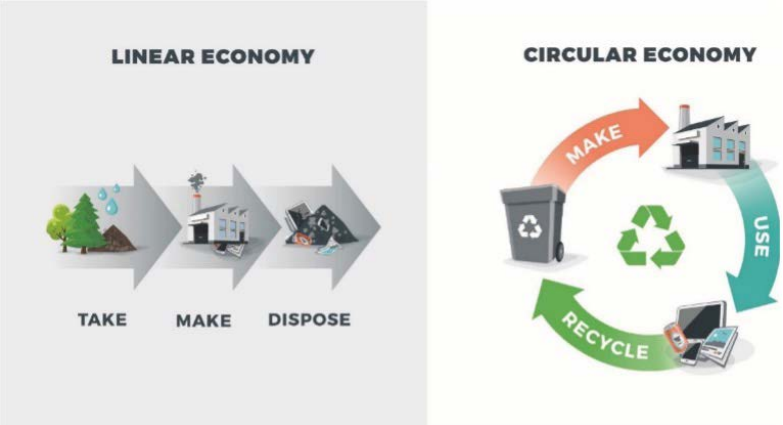
The formation of the Core Team was greatly supported by the British Council / Newton Fund Researcher Links Workshop initiative, with initial collaboration between the UK, Malaysia, Mexico and Brazil first established through these workshops. These were organised by Dr Kok Siew Ng and Dr Elias Martinez-Hernandez and supported by Prof Denny Ng and Dr Jorge Arturo Aburto Anell, with the British Council / CONACyT Researcher Links UK-Mexico Workshop in Mexico City focusing on *"Biorefinery research – Promoting International Collaboration for Innovative and Sustainable Solutions"*, and the British Council / Newton Fund Researcher Links UK-Malaysia Workshop in Kuala Lumpur exploring "*Bioenergy, Biorefinery and Bioeconomy: Promoting Innovation, Multidisciplinary Collaboration and Sustainability"*.

2. A Systems Approach to Sustainable Resource Management

Efficient strategies for organic resource recovery and valorisation are needed to improve resource efficiency and promote the transition from a linear "take-make-dispose" model towards a sustainable and circular bioeconomy **[Figure 1]**. The SYNERGORS project adopted an innovative systems approach **[Figure 2]** (i.e. integrated and multidisciplinary collaboration), working with more than 10 representatives from academia, industry and government to achieve these goals. Making progress towards these goals required the application of systems thinking approach, taking into consideration the interrelationship among various elements to understand the overall impact (technical, economic, environmental and social dimensions) on the whole system to ensure that the system is sustainable while avoiding any risk shifting and missed opportunity for resource recovery.

Definition of systems thinking

Systems thinking involves the consideration of **multiple perspectives** at its core, the **interconnectedness** of the different associated components constituted to a problem and **multi-stakeholder collaboration** to tackle complex problems and decision-making. (Ng and To, 2021)



Principles of Circular Economy[1]

- Eliminate waste and pollution
- Keep products and materials in use
- Regenerate natural system

Figure 1: *Transformation of a linear to circular economy model for resources and waste management*

In this project, a series of research studies have been conducted and categorised into the three main themes shown below. These studies involve the design and analysis of highly efficient and sustainable systems using:

- ***systems engineering approach***: design and analysis methods using computational modelling and optimisation approach;
- ***process integration technique***: a holistic approach to process design which enables the maximisation of resource efficiency through considering interactions between processes;
- ***sustainability assessment*:** comprehensive evaluation of economic, environmental and social impact and performance of the systems to ensure that the systems are economically compelling, environmentally benign and socially acceptable.

Theme 1: Strategic analysis for sustainable organic resources and waste management to achieve circular economy and net zero

Theme 2: Development of novel resource recovery and valorisation technology concept

Theme 3: Development of innovative biorefinery system design

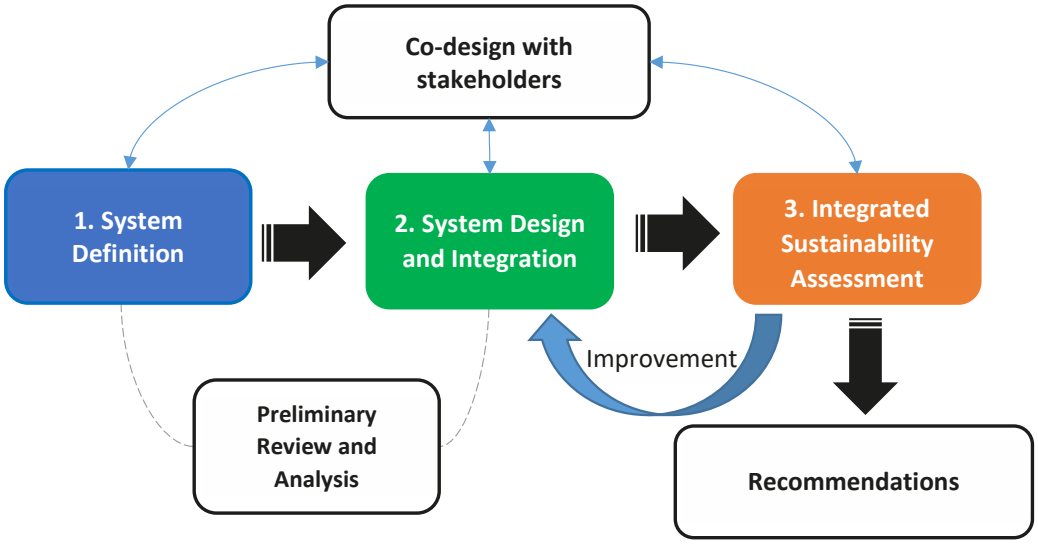


Figure 2: *A systems approach to sustainable resource management adopted in the SYNERGORS project.*

Unlocking the full potential of utilising organic waste requires a macro-level design concept **[Figure 3]** considering sources and nature of waste, types of recovery/valorisation technologies and product generation. Valuable resources embedded in organic waste streams can potentially be upgraded into a range of value-added products such as fuels, chemicals and polymers using different technologies combined in the form of polygeneration sites known as biorefineries.

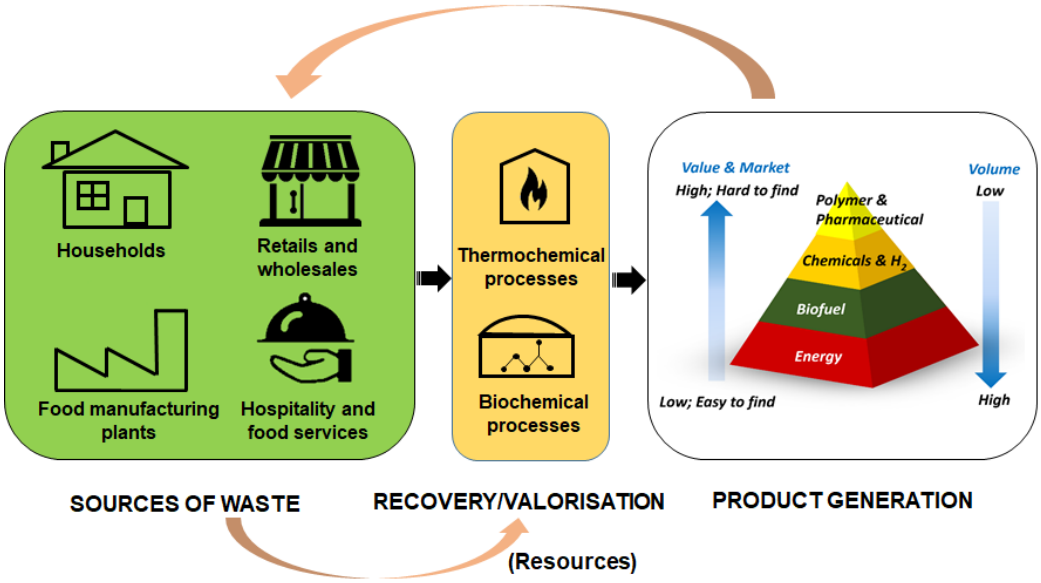


Figure 3: *A macro-level system design concept for resource recovery from waste via biorefinery approach to achieve circular economy*

Novel approaches have been proposed for sustainable industrial system design and strategic analysis for sustainable resource management:

- Advanced industrial system design using an innovative polygeneration[2] concept **[Figure 4]** i.e. a highly integrated system design for simultaneous production of fuels, chemicals and energy which could enhance resource efficiency and product diversification through its highly flexible and robust system configuration, has been proposed and demonstrated in biorefinery[3],[4] , CO_2 capture and utilisation[5] and waste-to-hydrogen[6],[7] systems.
- Strategic analysis has also been conducted on urban system using the Systems Thinking Approach to Resource Recovery (STARR) framework which consists of policy analysis, material flow analysis, scenario creation and sustainability assessment. The framework has been adopted to (i) systematically analyse the potential of recovering food waste in the UK via different configurations and synergistic resource management between households and supermarkets; and (ii) improve resource efficiency by considering energy supply and demand, waste management and resource recovery from waste in a single system.

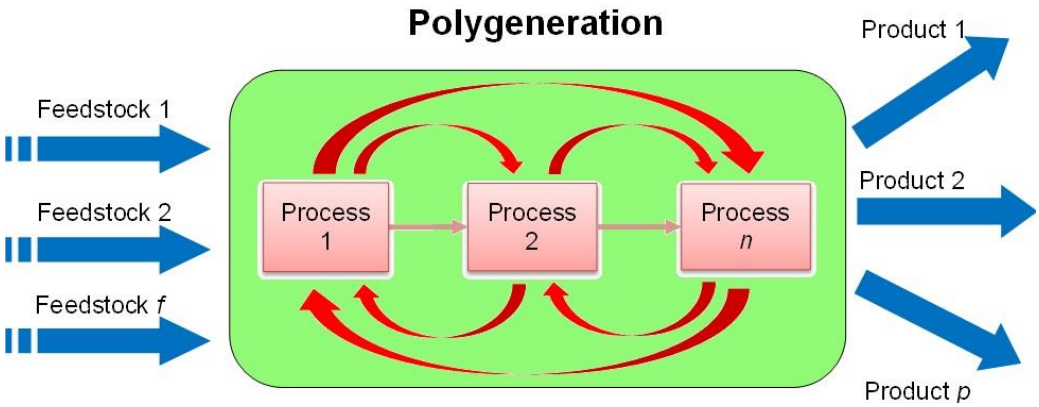


Figure 4: *Applying polygeneration strategies in process design enables efficient sharing of materials and energy, enhanced diversity in product generation, and offering higher flexibility, optimality and circularity in resource utilisation.*

3. Team Profiles

Principal Investigator

Dr Kok Siew Ng

UKRI/NERC Industrial Innovation (Rutherford) Research Fellow
Lecturer in Chemical Engineering
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Research Interests: Biorefinery system design; Decarbonised polygeneration system design; Resource recovery from waste; Circular economy

Dr Kok Siew Ng is the Principal Investigator of the UKRI/NERC SYNERGORS project (~£0.5 million, 4 years, Jan 2018-Dec 2021). He is a chemical engineer by training with extensive research and industrial consultancy experience in systems engineering, process integration, techno-economic analysis and environmental life cycle assessment (LCA). His research vision is to develop novel and sustainable solutions from a systems engineering perspective, to facilitate the transition of the chemical, energy and waste industries from a fossil-based, linear system to one that is fundamentally sustainable by using renewables as the mainstream resources and by fully embracing circular economy principles. Kok Siew has further contributed to a successful bid of Oxford to the NERC Changing the Environment programme (2022-2027) with a value of £10 million. He is the Co-Investigator (Co-I) for one of the sub-projects (Sprint 2) leading the techno-economic assessment of resource recovery from waste technologies. Kok Siew has contributed to more than 10 UK and international projects funded by NERC, Innovate UK, EU FP7, Royal Academy of Engineering and Newton Fund. His research is significant in terms of addressing global challenges in the 21st century, aligned with the UN SDG 7 and 12, the UK Industrial Strategy, and international ambitions to achieving circular economy and net-zero target.

Kok Siew has published more than 30 articles including journals, book chapters and magazine article, and have co-authored an advanced textbook “Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis”. His work related to decarbonisation of energy systems has been recognised by the IChemE Junior Moulton Medal award (best publication) in 2011. He is an Editorial Board Member of Resources, Conservation & Recycling Advances (RCR Advances) journal and also a reviewer for French ANR and UKRI/EPSRC proposals.. Kok Siew is enthusiastic in establishing international collaboration with researchers from multidisciplinary background. He has been working closely with international academic and industrial organisations in the UK, Europe, China and South East Asia. He has organised and participated in a number of British Council/Newton Fund workshops in Malaysia, Mexico, Brazil, Kazakhstan and China, and attended the Royal Academy of Engineering Frontiers of Engineering for Development Symposium “From feeding people to nourishing people”. He has a long-term ambition in influencing resources and waste management practices in developing countries towards sustainable development.

3.1 SYNERGORS Core Team

Professor Ir. Dr. Denny K. S. Ng is Associate Head, School of Engineering and Physical Sciences, Heriot-Watt University, Malaysia. Prof Ng is well published with over 200 papers and an h-index of 39. His areas of specialisation include optimisation of sustainable value chain of palm oil industry, energy management, resource conservation via process integration techniques, synthesis and analysis of biomass processing and integrated biorefineries. He is active in various professional bodies, which include IChemE, Young Scientist Network - Academy of Sciences Malaysia (YSN-ASM), etc. He is also the Chair of Academic Research on Palm Oil Sustainability (ARPOS). Prof Ng is also serving as technical committee in reviewing Malaysia Sustainable Palm Oil (MSPO) standard. With his excellence contributions, he received various international and national recognitions, which include the recent Tan Sri Emeritus Professor Augustine S H Ong International Special Award on Innovations and Inventions in Palm Oil (Young Scientist) 2021. Apart from focusing on research and development (R&D), Prof. Ng has also applied his R&D output in industrial consultation projects. To date, Prof. Ng has received more than RM 2.5 million research grants from government and industries to develop his research and commercialise the outputs.

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Professor Francisco Gaudencio M. Freires was born in Fortaleza (state of Ceará - Brazil) in 1974. He holds a degree in Civil Engineering from the Federal University of Ceará (1996), a Master's degree in Production Engineering from the Federal University of Santa Catarina (2000) and a Ph.D. in Industrial Engineering and Management from the Faculty of Engineering of the University of Porto (2007). He has experience in Production Engineering with emphasis on Business Logistics and Operations Management, working mainly on the following topics: Supply Chain Management, Reverse Logistics, Sustainable SCM, and Cost Management. He was a professor at the Federal University of the São Francisco Valley (UNIVASF) until 2011. He researched the issue of logistics and supply chain management of biofuels and fruit growing in the northeastern semi-arid region of Brazil. He has also developed research in the advance of the intermodal logistics of the São Francisco River and reverse logistics systems for empty pesticide packings. He is currently an Associate Professor in the Department of Mechanical Engineering at the Federal University of Bahia (UFBA) Polytechnic School. He also works in the Graduate Program in Industrial Engineering (PEI) at UFBA, currently researching renewable energy alternatives from the perspective of Supply Chain Management and Circular Economy.

Dr Eleni Iacovidou is a Lecturer in Environmental Management at Brunel University London, leading teaching on environmental governance, management and sustainable development. Her research work focuses on resources and waste management systems assessment and evaluation. She develops and employs systems-based valuation frameworks for streamlining the life cycle sustainability assessment of resource recovery systems and is an expert in identifying and evaluating radical and innovative interventions using multi-dimensional metrics. Her research supports policy, and decision-making processes and consults several groups on ways to integrate 'circular' with sustainable approaches. She is a chemist by background, with expertise on environmental engineering and environmental management research following studies at the Department of Chemistry, University of Crete and the Centre for Environmental Policy, Imperial College London.

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Anongnat (Annie) Somwangthanaroj is an Associate Dean in Research Affairs, Faculty of Engineering as well as a full professor at the Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Thailand. Annie obtained a Bachelor degree (2nd class honours) in Materials Science, Faculty of Science, Chulalongkorn University, Thailand in 1996. She obtained both Master and Doctorate degree in Macromolecular Science and Engineering, University of Michigan, Ann Arbor, MI, USA in 1999 and 2003, respectively. After graduation, she became a research scientist at College of Pharmacy, University of Michigan for a year before returning back to Thailand to become a lecturer at the Department of Chemical Engineering, Chulalongkorn University. Her research focuses on bioplastic packaging for extending shelf life of fresh produces and processed food, polymer processing, adhesive for electronics industries, nanocomposites, and zinc-based batteries. Annie founded Garden Fresh, a spin-off startup in November 2018. Garden Fresh offers biodegradable plastic bags that can extend shelf life of fresh produce up to five times of its shelf life. During the first wave of Covid-19 pandemic in Thailand, there was a lack of high-quality masks for medical frontlines. Therefore, Annie and her team researched, designed and produced the half face respirator and then co-founded CUre Enterprise, a spin-off in March 2021.

Katie Chong is a Lecturer in Chemical Engineering and EBRI Director of Research Outputs at Aston University. Katie has a particular interest in the thermochemical conversion of biomass and wastes, biorefinery process synthesis and techno-economic evaluation. Katie has 19 years' experience in the commercial and academic sectors working on bioenergy and process optimisation. In particular Katie likes to make techno-economic and environmental assessment data more accessible for the non-expert, to demonstrate the benefits of bioenergy and the circular economy. Katie is currently a Topic Group Representative for Conversion within the Supergen Bioenergy Hub, Regional Chair for the biomass and wastes special interest group of the Fuel and Energy Research Forum and is a committee member of the IChemE Clean Energy Special Interest Group and a founding member of The Society of Circular, Regenerative and Sustainable Systems (CRES).

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Dr David Tompkins
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SUEZ SES UK & Aqua Enviro, UK.

David is an environmental scientist with a background in digestate and compost market development, food safety, soil science and horticulture. David delivers technical consultancy on bioresources and anaerobic digestion, and is part of the senior management team at Aqua Enviro (a UK consultancy owned by the global SUEZ group), setting strategic business priorities, developing new services and supporting staff development. David has worked with composts and digestates since 2003 and wastewater since 2015. As a consultant David helps to assess market potential for waste-derived materials, and to navigate clients through the UK's regulatory maze – mapping pathways to end of waste for novel organo-mineral fertilisers and other products. David represents CIWM on the EA Sludge Strategy, sits on the ADBA digestate working group, and acts as an advocate for digestate within the regional BioVale AD Special Interest Group.

Dr Long Seng To is a Lecturer in Resilient Energy Systems and Co-Director of the Centre for Sustainable Transitions: Energy, Environment and Resilience (STEER) at Loughborough University. She has an interdisciplinary background with a BEng in Photovoltaic and Solar Energy Engineering, a BA in History and Philosophy of Science, and a PhD that spans both disciplines. She holds an Engineering for Development Research Fellowship from the Royal Academy of Engineering which focuses on enhancing community energy resilience using renewable energy in the Global South with research partners in Nepal and Malawi. Long Seng is Co-Investigator of the Modern Energy Cooking Services (MECS) programme where she leads work on modern energy cooking services in humanitarian and institutional settings, and Co-Investigator of the CESET project which focuses on community energy in Ethiopia, Malawi and Mozambique. She is Chair of the Solar Subgroup of the UN Economic Commission for Europe's Expert Group on Resource Management, Renewables Working Group where she leads work on the UN standard for solar energy resource classification.

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Dr Anh N. Phan
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Dr Anh N. Phan (Senior Lecturer in Chemical Engineering) has research expertise in reactor engineering/process intensification, process and product development and chemical/material recycling from waste. She has published more than 60 papers in these areas in high-impact journals and two book chapters (H index of 28). Since 2013, she has successfully supervised 8 full-time PhD students and 4 Research Associates/Assistants and currently leads a group of 12 researchers (PhD and postdoctoral researchers). Her research group focuses on hydrogen production from waste and residues, chemical recycling from plastic waste, process development and carbon materials from waste for water treatment and CO_2 removal. She is a reviewer for international journals: Chemical Engineering, Fuel, Biomass and Bioenergy, Bioresource Technology etc. She is a guest editor of Energies (impact factor: 2.707) and an Associate Editor of the IET Renewable Power Generation.

Professor Eileen Yu holds the Chair of Electrochemical Engineering in the Department of Chemical Engineering, Loughborough University, UK. After obtaining her PhD from Newcastle University pioneering on the development of direct methanol alkaline fuel cells, she worked as a research fellow at Max Planck Institute for Dynamics of Complex Technical Systems, Germany before she returned to Newcastle University to take up a prestigious EPSRC Research Fellowship (Life Science Interface). This fellowship enabled her to extend her research into the biosciences, from which she has developed a multidisciplinary research programme.

She has a wide range of experience in various fields in electrochemical and bioelectrochemical systems for energy, environmental and biomedical applications. She has attracted more than £20m funding from various funding organisations. Her current research includes understanding fundamentals and engineering applications of electrocatalysis and microbial electrosynthesis for CO_2 utilisation, resource recovery from wastes, bioremediation and environment monitoring with bioelectrochemical systems.

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Prof. Ir. Dr. Wan Azlina is currently Head of Sustainable Process Engineering Research Centre (SPERC) at the Universiti Putra Malaysia. Her research interests focus on the sustainable chemical valorisation of biomass and waste valorisation to bioenergy, biofuel and biomaterials. To date, she and her team have received research grants worth MYR 4Million including an international grant (NEWTON FUND) and industrial consultation projects. She has published vastly in reputable journals and conference proceedings (>300) and she is the recipient of prestigious awards including Malaysia's L'oreal Fellowship for Women in Science (FWIS). She has also been involved as technical expert panels for various governmental agencies namely the Ministry of Housing and Local Government (MHLG), Department of Environment (DOE) and Department of Standard Malaysia (DSM) in consulting waste-to-energy (WTE) projects and developing standards for biomass as solid fuel in Malaysia. Furthermore, she has been involved in several professional associations namely the Chemical Engineering Technical Division (CETD), Institute of Engineers Malaysia (2014-2016) and Young Scientist Network (YSN)(2018-2022). As a YSM member, her active commitments in the review and formulation of several National Policy in Science, Technology & Innovation (NPSTI) enriches her knowledge and skills in dissecting key contemporary international and regional science policy issues related to future studies, waste management, while intimating how science, technology, and innovation contribute to policy developments, global governance and sustainable development of communities around the world.

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Dr Elias Martinez Hernandez is a researcher at the Biomass Conversion Division of the Mexican Institute of Petroleum. He obtained his first-class degree in Chemical Engineering from UNAM (Mexico) and his PhD from the University of Manchester (UK) working on process integration, economic and environmental assessment of biorefineries. He then worked as a Research Fellow at the University of Surrey and at the University of Oxford working on integrated production systems based on locally available renewable resources and the food-energy-water nexus. Dr Elias was a lecturer in the Department of Chemical Engineering of the University of Bath before joining IMP. He is a co-author of the book 'Biorefineries and Chemical processes – Design, Integration and Sustainability Analysis' as well as multiple peer-reviewed journal publications.

His areas of interest comprise process systems engineering applied to waste processing in biorefineries, food-energy-water nexus, life cycle assessment and sustainable chemical process design.

Rashmi works as a Senior Research Scientist at Anaero Technology Ltd. She completed her MSc in Water and Wastewater Engineering from Cranfield University in 2014. In her current role at Anaero she is involved in a range of in-house and collaborative research projects involving anaerobic digestion of food waste, agricultural residues, agro-industrial waste and other novel feedstocks with academia and industry. She is also responsible in liaising with the industry clients and delivering training on carrying out BMP tests. She is actively involved in supervising MSc students every year based at Anaero's research facility. She is currently pursuing her PhD in Chemistry at University of York to extend her research interest whilst working at Anaero. Her research is focused on exploitation of renewable resources for high value chemicals and bioenergy production. She intends to use fermentation and anaerobic digestion to extract selected biobased chemicals and explore the nature and biogas potential of the selected underutilised agricultural residues. She also aims at exploring physical, chemical and biochemical methods to deconstruct selected lignocellulosic to extract biobased chemicals and bioenergy as part of her study.

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Dr Khemmathin (Martin) Lueangwattanapong is a lecturer at the Department of Science and Technology, Muban Chombueng Rajabhat University, Thailand. He previously worked as a research scientist at the Excellent Center of Waste Utilization and Management (ECoWaste), the King Mongkut's University of Technology Thonburi, Bangkok, Thailand. He received an MEng degree in Chemical Engineering from Imperial College London in 2016 and graduated from the University of Oxford with a degree in Engineering Science. His DPhil work focused on the potential of Crassulacean Acid Metabolism plants as biomass for bioenergy and biorefinery. The research was part of the dryland bioenergy project funded by the Oxford Martin School.

His research interests include waste utilisation and valorisation, plastic waste management, bioenergy and biorefinery, anaerobic digestion, and circular economy.

Other Members of the Core Team

- Professor Aidong Yang, University of Oxford, United Kingdom
- Professor Natalia Yakovleva, KEDGE Business School, France
- Mr Edgar Blanco, Anaero Technology, United Kingdom
- Dr Jorge Arturo Aburto Anell, Instituto Mexicano del Petróleo (IMP), Mexico

3.2 SYNERGORS Student Associates

Name	Institution	Country	Degree	Year	Dissertation Title
Hannah Kargbo	Newcastle University	UK	PhD	2019-2022	Biofuel production from biomass waste and residues
Enzia Schnyder	University of Oxford / University of Nottingham	UK	MEng	2018/19	Modelling the potential of chemical production from food waste using anaerobic digestion (Awarded the best 4YP Prize)
Mario Büttner	Aachen University / BP	Germany	MSc	2019/20	A systems thinking framework for sustainable airport development
Meléa Emunah	Princeton University	US	MEng	2019/20	Applying a systems thinking approach to enhancing circularity in water management systems: A case study of San Francisco, CA, USA
Danial Farooq	University of Oxford / UCL and Rutherford Appleton Laboratory	UK	MEng	2019/20	Development of hydrothermal liquefaction process for the production of sustainable aviation fuel in the UK
Zakaria Jama	University of Oxford	UK	MEng	2020/21	A system thinking approach to sustainable management of magnesium in the United States
Lyn Yeoh	University of Oxford / Equinor	UK	MEng	2020/21	Investigating the future prospects of spent coffee ground valorisation using a biorefinery approach
Patricia Jacob	University of Oxford (Physics)	UK	MEng	2020	Software development
David Clarke	University of Oxford (Mathematics)	UK	MEng	2020	Software development
Minakshi Ashok	University of Oxford (Engineering Science)	UK	MEng	2021	Software development
Luke Hatton	University of Oxford (Engineering Science)	UK	MEng	2021	Editorial

4. Achievements of SYNERGORS

The findings of SYNERGORS have been disseminated through academics publications, a number of engagement activities, the creation of the Society of Circular, Regenerative and Sustainable Systems (CRES), and several international visits and case studies.

1. Publications

The SYNERGORS project resulted in 9 academic publications, including:

- 7 journal articles, in high impact academic journals such as *Renewable and Sustainable Energy Reviews*; *Resources, Conservation & Recycling*; and the *Journal of Cleaner Production*;
- 1 book chapter in "Towards Sustainable Chemical Processes"; and
- 1 magazine article in The Chemical Engineer (TCE).

2. New experimental studies on chemical production from food waste with Anaero Technology

3. Engagement activities

Dr Kok Siew Ng has

- organised and chaired 2 project workshops at the University of Oxford, bringing together members of the SYNERGORS Team from across the UK and the world;
- presented his research findings at the *27th European Biomass Conference & Exhibition (EUBCE)* in Lisbon, and at 2 British Council UK-China Researcher Links Workshops in Beijing and Tibet (*Sustainable Systems for CO_2 Utilisation, and Renewable Energy Systems in Zero Carbon Villages*)
- participated and contributed to discussions in 10 other meetings, workshops and events for knowledge exchange and networking, including the *Westminster Energy, Environment and Transport Forum; Frontiers of Engineering for Development* organised by the Royal Academy of Engineering; UKRI and Innovate UK workshops; and a visit by the *Harbin Institute of Technology*.

A full list of event is provided in Section 7.

4. International visits and case studies

Dr Kok Siew Ng has

- Visited Malaysia to promote sustainable resources and waste management and circular economy; including courtesy visit and initiate collaboration with Universiti Putra Malaysia (UPM), Heriot-Watt University Malaysia, Solid Waste and Public Cleansing Management Corporation (SWCorp), National Solid Waste Management Department (JPSPN), Penang Green Council, Penang Hill, Higher Education Malaysia Association (HEYA), Petaling Jaya City Council.
- Visited Thailand to initiate collaboration with Chulalongkorn University.
- Conducted preliminary scoping studies for Brazil and Mexico, collaborating with Universidade Federal da Bahia (UFBA) in Brazil and Instituto Mexicano del Petróleo (IMP) in Mexico.

5. Creation of the Society of Circular, Regenerative and Sustainable Systems (CRES): A knowledge exchange platform to promote systems thinking & circular economy

5. Publications and Summary of Research Findings

Theme 1: Strategic analysis for sustainable organic resources and waste management to achieve circular economy and net zero

1.a Sustainable waste management through synergistic utilisation of commercial and domestic organic waste for efficient resource recovery and valorisation in the UK[8]

Authors: Kok Siew Ng, Aidong Yang, Natalia Yakovleva
Journal: Journal of Cleaner Production

The UK faces significant challenges in tackling the amount of food waste that is currently sent to landfill. Most of the policy focus and discussions to date have been on the prevention of household food waste - with commercial food waste often overlooked - and there are opportunities to improve recovery of useful materials and energy from food waste through more effective waste management. The objective was to identify and present a framework for sustainable management of organic waste and recovery in the UK in this publication. In order to develop a framework for sustainable waste management, this publication followed the STARR (Framework for Systems Thinking Approach to Resource Recovery, **[Figure 5]** approach, which has been developed based on circular economy principles, industrial ecology and design for sustainability. This included an examination of the flow of resources **[Figure 6]** within households and supermarkets and the creation of scenarios with appropriate technologies and resource utilisation strategies to manage these flows. The findings show significant economic, environmental and social benefits of undertaking a circular economy approach, with systems thinking at its core, to addressing waste problems.

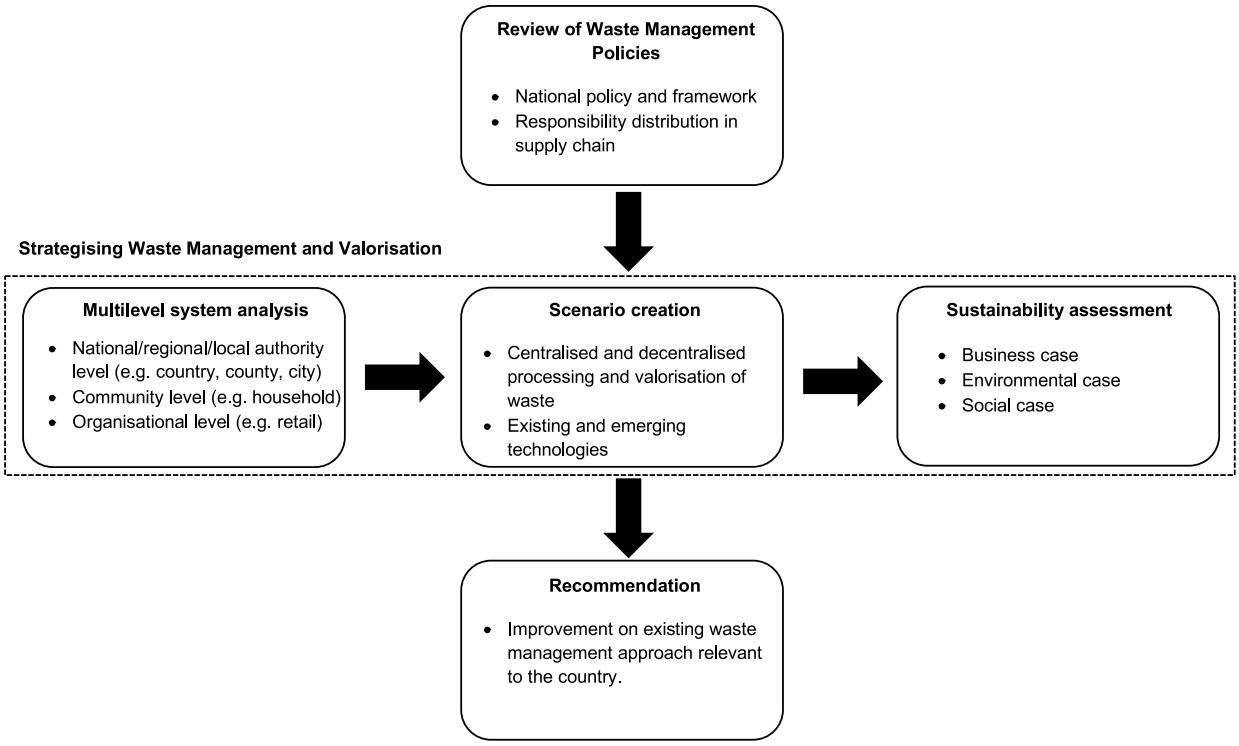


Figure 5: *Framework for Systems Thinking Approach to Resource Recovery (STARR)*

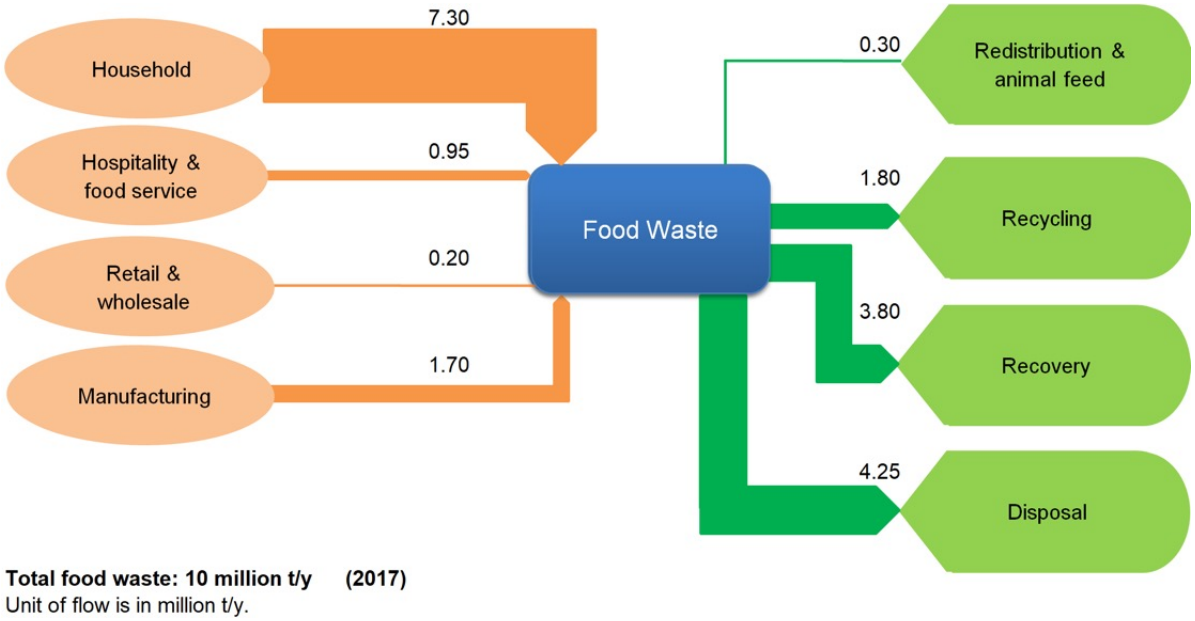


Figure 6: *Material flow analysis of food waste generation from the UK post-farm gate sectors and distribution. Data is obtained from WRAP (2017)*[9].

1.b A systems thinking approach to stimulating and enhancing resource efficiency and circularity in households[10]

Authors: Kok Siew Ng, Long Seng To
Journal: Journal of Cleaner Production

Households are highly energy and resource intensive, and waste generation and management in domestic households has significant implications at the national level when aggregated. Addressing energy and waste issues independently at the household level without a holistic understanding of the problems and interdependencies may lead to inefficient use of resources. This publication aimed to develop a system thinking approach to circular economy at a household level, which takes into

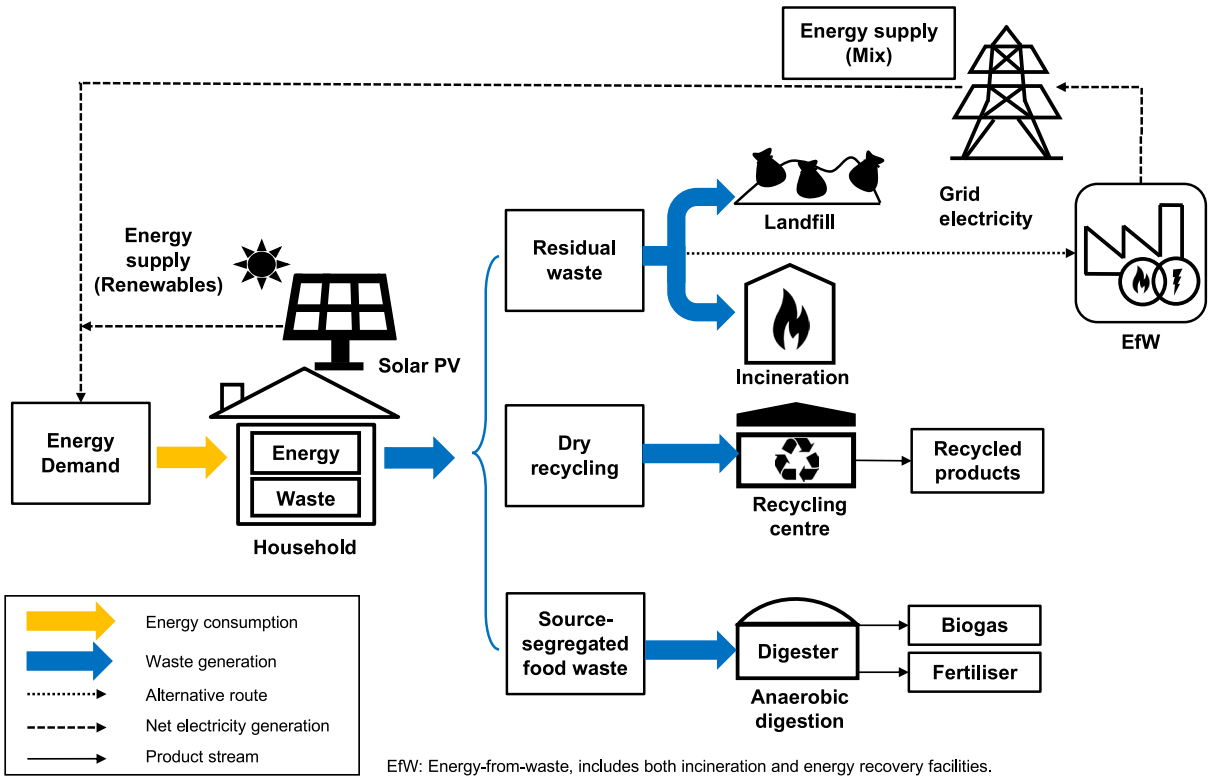


Figure 7: *Household Systems Thinking Mind Map*

consideration energy supply and demand, waste management and resource recovery from waste **[Figure 7]**, which has so far not been examined. The STARR framework **[Figure 5]** was adopted to examine household resource management. Material flows of waste and energy flows were constructed using Sankey diagrams, and scenarios of management were developed and compared to business-as-usual systems. The scenario with the least environmental impact involves adopting a concerted approach through switching to solar photovoltaics (PV), increasing the recycling rate and using electricity generated from residual waste. This resulted in a saving of 1308 kg of CO_2-eq per year and a saving of £680 per year on a one household basis. This gives a clear direction that greater technology adoption, behavioural change and a more supportive policy environment will be essential to realising transformational changes in resource utilisation and management.

1.c. Global biorenewable development strategies for sustainable aviation fuel production[11]
Authors: Kok Siew Ng, Danial Farooq, Aidong Yang
Journal: Renewable and Sustainable Energy Reviews

Air travel is a major mode of international travel and supports the global economy as a means of fast conveyance of products and people for tourism, trade, commerce and other activities. Aviation fuel is conventionally supplied from kerosene produced from crude oil, and as a result the aviation industry accounts for nearly 2% of global CO_2 emissions. There is a pressing need worldwide to improve the uptake of sustainable aviation fuels, and this publication aimed to review the current status of biomass-derived aviation fuels (*'biojet fuels'*) to identify areas for further improvements to meet the needs of the future aviation industry. This publication presented a comprehensive review of the state of biojet fuels and their uptake in the global commercial aviation industry, including state of the art certified technologies. The production routes and fuel specifications were initially outlined, and this is followed by a detailed discussion on selected production routes with a comparison of their techno-economic and environmental performance. Existing policies for reducing greenhouse gas emissions in the aviation industry were examined, and potential challenges with the uptake of biojet fuels were discussed. The main recommendations are: (i) the production of biojet fuel from lignocellulosic biomass and waste feedstock should be promoted instead of food/feed crops which have high indirect land use change emissions; (ii) feedstock and technologies for sustainable aviation fuel production should be selected based on production cost and environmental footprint, with the consideration of avoiding competition with the existing road transport biofuel market.

Theme 2: Development of novel resource recovery and valorisation technology concept

2.a Evaluating the techno-economic potential of an integrated material recovery and waste-to-hydrogen system[6]
Authors: Kok Siew Ng, Anh N. Phan
Journal: Resources, Conservation & Recycling

Household recycling waste in the UK is collected by local authorities and sent to material recovery facilities (MRF), which is currently the preferred method of treating recycling streams to recover value from waste. However, considerable amount of non-recyclable materials are rejected to landfill or energy-from-waste (EfW), and this has hindered maximum resource recovery from waste. This publication aimed to develop an integrated material recovery and waste-to-hydrogen concept **[Figure 8]**, which would enhance resource efficiency whilst also minimising environmental impact. Using the rejected non-recyclable materials in the gasification system could potentially offer significant savings on disposal costs whilst diverting a significant amount of waste from landfills. Due to the high market value of hydrogen, the integrated system generated 4 times more revenue than a conventional material recovery facility (though with higher capital costs), thus offering a promising alternative production route for renewable hydrogen and also diverting more waste from landfill.

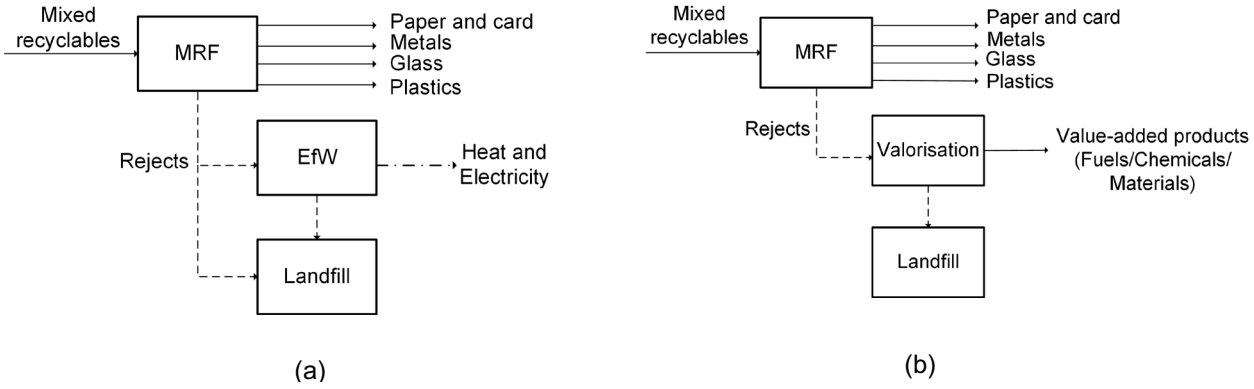


Figure 8: *(a) Conventional approach to mixed recyclable management, (b) Proposed integrated material recovery facility and valorisation of mixed recyclable stream*

2.b Techno-economic assessment of a novel integrated system of mechanical-biological treatment and valorisation of residual municipal solid waste into hydrogen: A case study in the UK[7]

Authors: Kok Siew Ng, Anh N. Phan, Eleni Iacovidou, Wan Azlina Wan Ab Karim Ghani

Journal: Journal of Cleaner Production

Resources are often not recovered effectively from waste, with most ending up in landfill or only being recovered as energy through energy-from-waste (EfW) facilities. Innovative strategies are thus urgently needed to maximise resource efficiency, divert waste from landfill and reduce reliance on EfW. This publication aimed to address this issue by proposing a novel treatment concept that combines material recovery and hydrogen fuel production as alternatives to energy-from-waste. This study compared the economic performance between a novel integrated mechanical-biological treatment (MBT) with valorisation system **[Figure 9]**, and a conventional MBT system. The new MBT system could potentially offset the high disposal cost of rejected materials in a conventional MBT system. The proposed system showed higher economic potential compared to the conventional system, at nearly 12 times the annual profit. The minimum hydrogen selling price was also estimated to be at £3.4/kg, which would allow it to compete with hydrogen produced from solar and wind electrolysis. The proposed system clearly offers an opportunity to improve resource recovery from waste, minimise waste disposal to landfill and reduce reliance from EfW, and future developments in advancing these systems should explore alternative integration pathways.

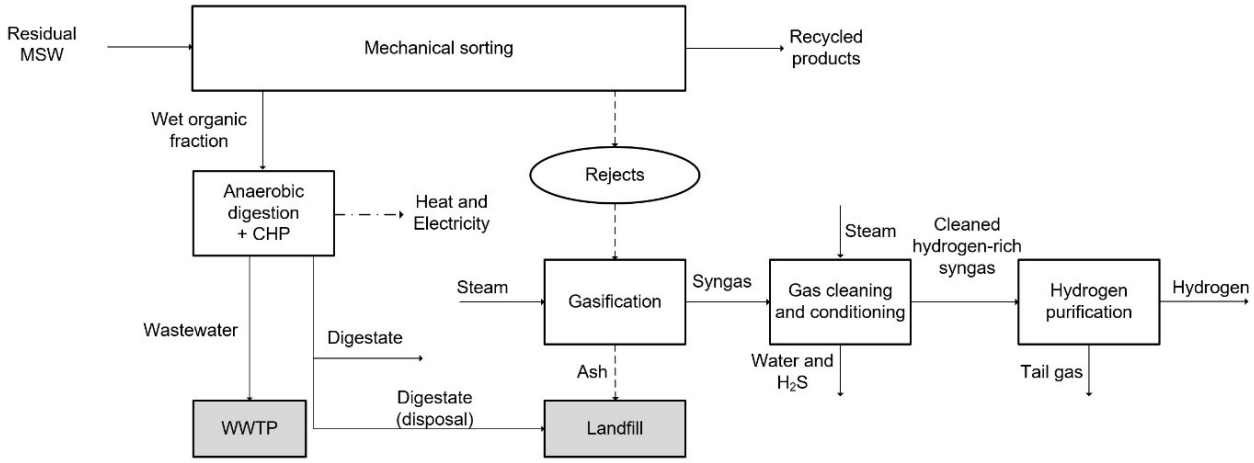


Figure 9: *Integrated mechanical-biological treatment and gasification system for material recycling, energy recovery and hydrogen production.*

Theme 3: Development of innovative biorefinery system design

3.a. Techno-economic assessment of an integrated bio-oil steam reforming and hydro-deoxygenation system for polygeneration of hydrogen, chemicals and combined heat and power production[3]

Authors: Kok Siew Ng, Elias Martinez-Hernandez
Book: Towards Sustainable Chemical Processes

Overexploitation of fossil fuels for the production of energy, fuels, and chemicals is causing severe destruction to the environment. Research into the use of cleaner and renewable sources of fuel is crucial for a transition to a cleaner society. Biomass is the only renewable source which contains carbon and is abundant across the world. This publication presented an integrated biorefinery system **[Figure 10]** for the generation of hydrogen, chemicals, and heat and power, and assessed its techno-economic feasibility. This publication followed a systematic conceptual process design framework, comprising process modelling, energy integration and economic analysis, to design the biorefinery system. The demonstrated system was shown to be energy self-sustaining, with the combined heat and power production providing the required steam and power for other processes. The design adopted a polygeneration configuration for multiple product generation, and is highly integrated and flexible, ensuring maximum resource efficiency and economic performance while minimising the environmental impact. This offered a clear alternative to fossil fuel-based production of energy, fuels, and chemicals, that future work should explore more in depth.

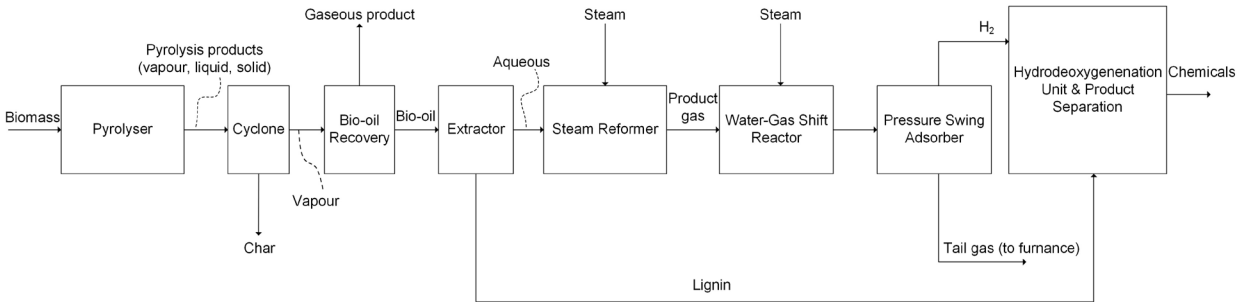


Figure 10: *Integrated biomass pyrolysis, steam reforming and hydrodeoxygenation system*

3.b. Exploring the feasibility of producing sustainable aviation fuel in the UK using hydrothermal liquefaction technology: a comprehensive techno-economic and environmental assessment[12]

Authors: Danial Farooq, Ian Thompson, Kok Siew Ng
Journal: Cleaner Engineering and Technology

Carbon emissions from the aviation industry are a significant concern, given the projected doubling in global passenger numbers by 2050. The adoption of sustainable aviation fuel has the potential to mitigate the environmental impacts by minimising the carbon emissions from aviation travel. This publication examined the feasibility of a hydrothermal liquefaction plant in the UK, which would use organic waste to produce sustainable aviation fuel. This study also considered heat integration and resource recovery from by-product & residue streams within a hydrothermal liquefaction plant **[Figure 11]**. A plant with a capacity of 10,000 kg/hr was designed, with the lowest overall greenhouse gas emissions and minimum fuel selling price found for sewage sludge-based jet fuel when compared to algae or food waste used as a feedstock. Regional assessment using geographic information system (GIS), **[Figure 12]**, indicated that nearly a quarter of the UK jet fuel demand could be met with integrated hydrothermal liquefaction technology drawing upon locally available organic resources. The carbon footprint assessment demonstrated that with maximum production, the technology could result in a 18.3% reduction of CO_2 emissions relative to current aviation emissions.

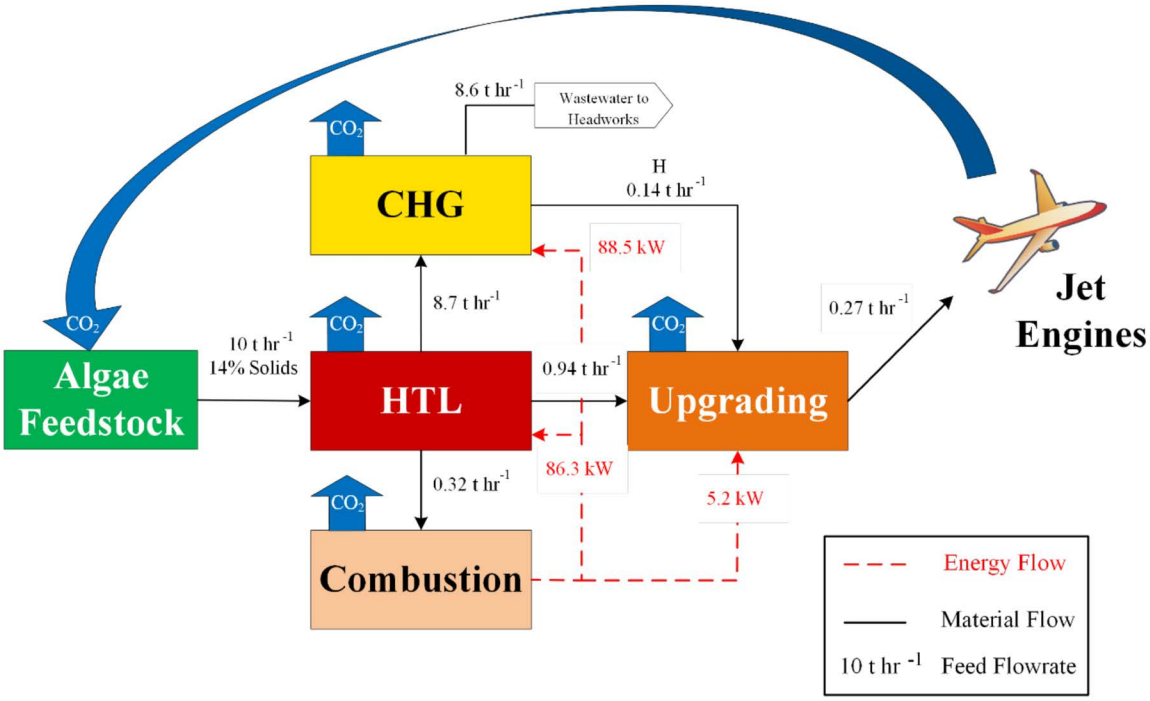


Figure 11: *Process flow diagram for the proposed hydrothermal liquefaction plant, which would run on an algae feedstock*

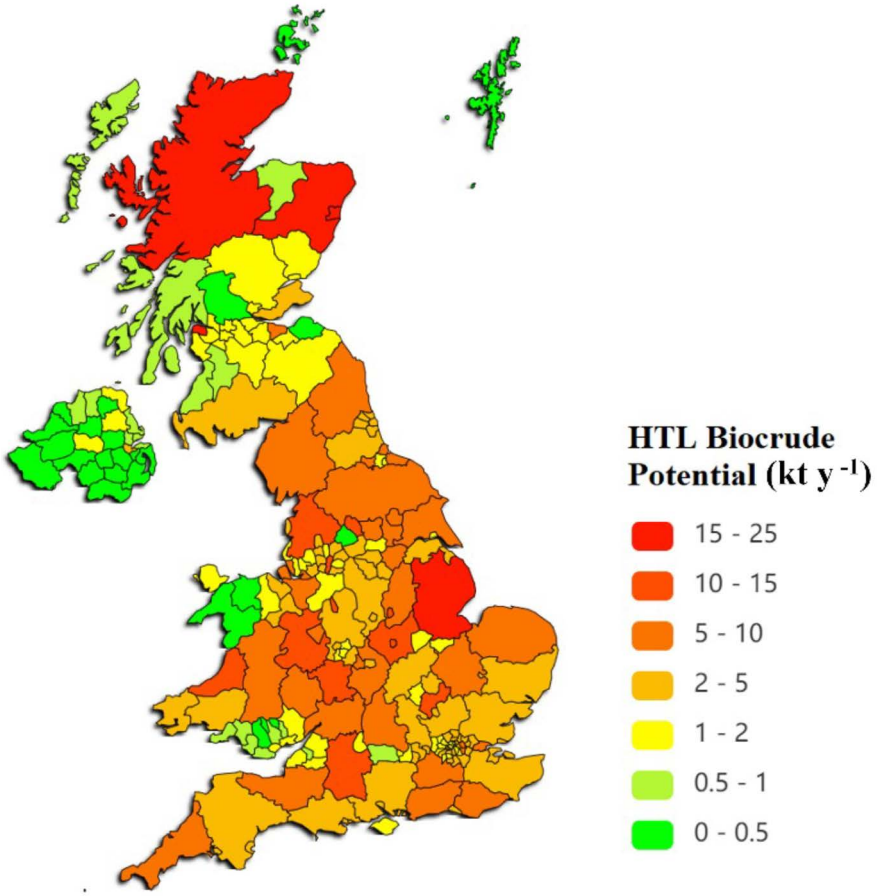


Figure 12: *GIS Map for the UK indicating the biocrude production potential from hydrothermal liquefaction plants utilising localised organic waste feedstock including food waste and sewage sludge*

3.c. Future prospects of spent coffee ground valorisation using a biorefinery approach[13]

Authors: Lyn Yeoh, Kok Siew Ng
Journal: Resources, Conservation & Recycling

In the UK, half a million tonnes of spent coffee ground waste are generated annually, most of which go to landfill or energy-from-waste plants. This publication aimed to investigate the prospect of biorefineries which would use spent coffee grounds, assessing the impact of biorefinery size, location and productions on economic and environmental performances. Two biorefinery system configurations were proposed **[Figure 13]**. The first design (Configuration I) was based on a well-research pathway combined with current practices, whilst the second design (Configuration II) incorporated more novel methods for the production of high value chemicals. Four scenarios were generated, with different combinations of size, design configuration, and location relative to the feedstock. The scenario where the biorefinery is located within the coffee factory site was found to have the lowest greenhouse gas emissions. The economic viability of the biorefinery systems was found to be very sensitive to the product price fluctuations. Overall, the results of this study indicated that future spent coffee ground biorefineries have the potential to produce multiple high-value chemicals and to meet the growing biodiesel demand, with similar production costs and lower greenhouse gas emissions when compared to conventional biodiesel.

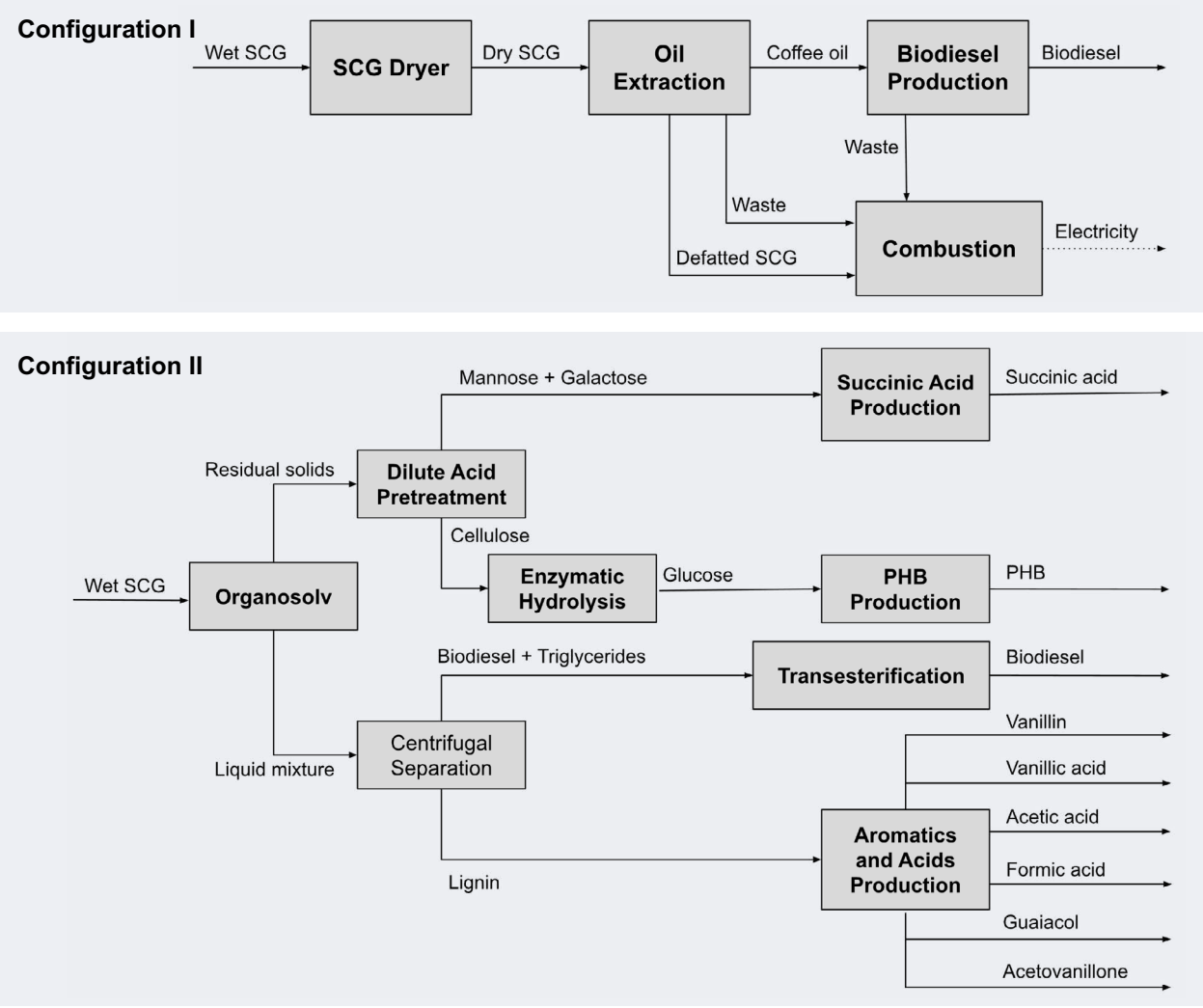


Figure 13: *Biorefinery approach to spent coffee ground valorisation. Configuration I: biodiesel and electricity production; Configuration II: biodiesel and chemical production.*

6. New Experimental Studies on Chemical Production from Food Waste

As part of the SYNERGORS research project, Dr Kok Siew Ng collaborated with Anaero Technology to investigate chemical production from mixed food waste. Anaero Technology aims to improve access to anaerobic digestion research and optimisation whilst driving research standards up and was founded to address the need for equipment capable of evaluating the biogas or inhibitory potential of feedstock that are processed in full-scale anaerobic digestion plants.

Investigating chemical production from mixed food waste

Most of the conventional waste treatment facilities run on marginal profits and relying on governmental subsidies. The products generated such as digestate and biogas from anaerobic digestion of food waste have low market values and limited secondary markets. This is not sustainable in long term because the full potential of resource recovery has not yet been realised. In addition to serving as a treatment facility, anaerobic digestion can potentially be upgraded to generate value-added products such as volatile fatty acids (VFA). VFA has a wide range of applications in the pharmaceutical, food, drink and chemical industries as flavour components, preservatives, synthetic fibres and so on, as well as new applications in bioplastics production. SYNERGORS created a partnership with Anaero Technology who shares the same visions to work on experimental research in investigating the yield of volatile fatty acid formation from food waste by varying some operating parameters of digester. Anaero Technology is an equipment specialist for lab-based digester design and the company owns patented technologies such as the automatic feeding digester.

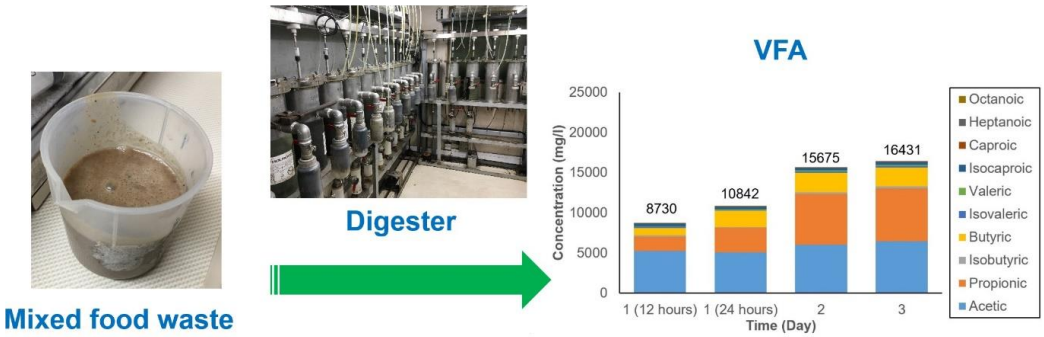


Figure 14: *Conversion of mixed food waste into volatile fatty acids via anaerobic digestion.*

7. Engagement Activities

1. Inaugural Meeting of SYNERGORS Project

The inaugural meeting of the SYNERGORS project took place on the 22nd-23rd of May 2018 and was hosted by Dr Kok Siew Ng at the Department of Engineering Science, University of Oxford. 14 participants from the academia and industry from the UK, Ireland, Malaysia, Brazil and Mexico attended the meeting to discuss collaboration plans for the SYNERGORS project. The meeting was aimed to enhance cross-fertilisation of ideas from various disciplines and promote long-term collaboration between the UK and developing countries. On the outcome of the inaugural meeting, Dr Ng commented "[It] was truly promising, with a coherent vision agreed by all delegates in adopting an innovative and collaborative approach to tackle global challenges in waste management".

2. British Council China-UK Workshop: Sustainable Systems for CO_2 Utilisation: from Innovation to Practical Implementation

The China-UK Workshop on Sustainable Systems for CO_2 Utilisation took place in Beijing, China across the 22nd-26th July 2018. This was organised as a collaboration between the Chinese Academy of Sciences and the University of Manchester, through the Researcher Links programme offered within the Newton Fund, the British Council and National Natural Science Foundation of China. This workshop discussed the challenges to implementation of systems for CO_2 utilisation. Dr Kok Siew Ng presented "*Sustainable industrial system design through carbon dioxide utilisation and polygeneration strategies*" at the workshop.

3. British Council China-UK Workshop: Renewable Energy Systems in Zero Carbon Villages

The China-UK Workshop on Renewable Energy Systems in Zero Carbon Villages took place in Lhasa, Tibet, China across the 6th-8th of August 2018. This was organised as a collaboration between the Xi'an University of Architecture and Technology and Cardiff University, through the Researcher Links programme supported by the Newton Fund, the British Council and National Natural Science Foundation of China. This workshop discussed topics of sustainable energy for all and how it impacts on the economic development and social welfare of people, particularly the vulnerable or those with lower incomes, in Tibet. Dr Kok Siew Ng presented "*Sustainable resource management and energy systems design through decarbonised polygeneration strategy*" at the workshop.

4. 27th European Biomass Conference & Exhibition

The 27th European Biomass Conference & Exhibition (EUBCE) took place on 27th – 31st May 2019 in Lisbon, Portugal. Dr Kok Siew Ng presented "*Organic Waste Valorisation through Polygeneration Strategies*", sharing his insights into the development of technological know-how on designing, integrating and analysing the system using a holistic approach in order to result in an economically competitive, environmentally benign and sustainable organic waste valorisation system.

5. Launch Event for the Society of Circular, Regenerative and Sustainable Systems (CRES)

The Society of Circular, Regenerative and Sustainable Systems was officially launched at the University of Oxford on the 3rd of February 2020, and was hosted at the Thatcher Business Education Centre, Saïd Business School. 25 representatives from the UK, Malaysia, Mexico, Thailand, Brazil and the Netherlands were invited to the launch event of the society to enable joint cross-disciplinary and cross-sectoral discussions. A series of keynote seminars provided insights into a systems thinking approach, followed by a breakout session in the afternoon to understand how CRES could help address various challenges in sustainable development.

Other Events (Participants)

Event	Location	Organiser	Date
Westminster Energy, Environment & Transport Forum Keynote Seminar: Priorities for UK waste and recycling policy and developing the circular economy	London, UK	Westminster Energy, Environment & Transport Forum	18th Jan 2018
H2020 Consortia Building Workshop: EU Funding for the Bio-Based Industries (BBI)	Glasgow, UK	Innovate UK/KTN	10th May 2018
Syntropic Agroforestry course	Spain	Soil-Sun-Soul	22-24th June 2018
Seminar on SDG12 Responsible Consumption and Production	London, UK	Newcastle University Institute for Sustainability and Newcastle University London	28th June 2018
Process Design Tools Training: SuperPro Designer	Reading, UK	BBSRC FoodWasteNet, University of Reading	13-14th September 2018
Flightplan for Sustainable Aviation	Edinburgh, UK	Heriot-Watt University; Low Carbon Jet Fuel (LCJF), EPSRC	13th June 2019
Visit by the Harbin Institute of Technology (HIT)	Oxford, UK	University of Oxford	2nd July 2019
ISCF Wave 3 Smart Sustainable Plastic Packaging: Enabling Research Scoping Workshop	Birmingham, UK	UKRI	15th November 2019
Expert Workshop: Potential of Hydrothermal Liquefaction (HTL) routes for biofuel production	Brussels, Belgium	HyFlexFuel	19th November 2019
9th Stakeholder Plenary Meeting of European Technology and Innovation Platform (ETIP)	Brussels, Belgium	European Technology and Innovation Platform (ETIP) Bioenergy	20-21st November 2019
Frontiers of Engineering for Development: From feeding people to nourishing people	Madagascar	Royal Academy of Engineering (RAEng)	27-29th November 2019

8. International Case Studies

As part of the SYNERGORS project, international research visits to Malaysia, Thailand, Brazil and Mexico were conducted to promote cross-disciplinary and cross-sectoral collaboration in circular economy for resources and waste management. Unfortunately, due to the Covid-19 pandemic, the visits to Brazil and Mexico had to be cancelled and so literature reviews were conducted in their place.

8.1 Malaysia

Dr Kok Siew Ng along with Dr Eleni Iacovidou spent two weeks in Malaysia in 2019 meeting with key stakeholders from government, academia, industry and NGOs to gain a better understanding of the country's waste management system and propose recommendations for addressing the multiple issues faced by the waste management sector.

During their trip the researchers met the Head of Department of Chemical Engineering at UPM University and visited the Sustainable Process Engineering Research Centre (SPERC), a newly established research centre at UPM pioneering the application of a systems approach in designing and integrating new industrial and waste valorisation technologies and processes. They also had the opportunity to meet the VC of Penang Green Council, YB Phee Boon Poh, who has introduced various initiatives including the banning of polystyrene packaging and introducing a partial ban on single-use plastic bags and has further plans to promote alternative options for municipal solid waste management.

Meeting with Penang Green Council. [Left to right: Dr Eleni Iacovidou (Brunel University London), YB Phee Boon Poh (Penang Green Council), Dr Kok Siew Ng (University of Oxford) and Mr Tze Howe Ooi (HEYA)].

At Malaysia's National Solid Waste Management Department (JPSPN), the Deputy Director General (Technical) of JPSPN provided the team with invaluable insights into the various issues and challenges relevant to municipal solid waste management in Malaysia, such as the importing of contaminated plastic waste.

During a visit to the Solid Waste and Public Cleansing Management Corporation (SWCorp) the researchers discussed illegal dumping of waste, landfill sites and imports of plastic waste with the Deputy CEO (Technical) and his team. SWCorp plan to promote initiatives aimed at increasing awareness of waste segregation at source, deposit return schemes and incentivising recycling.

The team made the most of their two weeks in the

Research visit to the Department of Chemical Engineering, Universiti Putra Malaysia

country, meeting with representatives from industry and visiting relevant sites, including:

- Touring the food waste recycling facility at Petaling Jaya, which processes around 500 kg of food waste per day by means of anaerobic digestion producing biogas and fertiliser.

- Visiting Penang Hill, one of the most popular tourist attractions in the area, which generates a significant amount of waste. Wastewater treatment facilities are being introduced at the site and there are plans to develop a more sustainable solid waste management system.

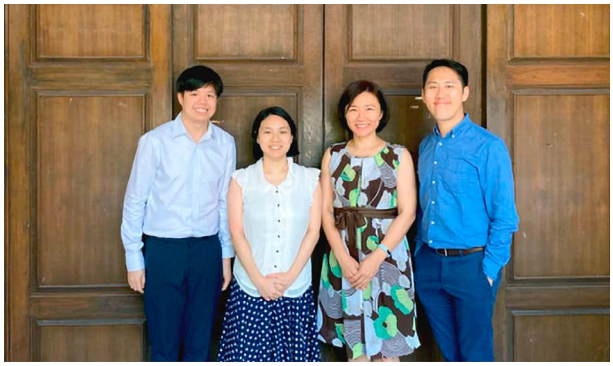
- Taking part in a knowledge exchange session at the Higher Education Malaysia Association (HEYA), a Malaysian NGO providing training to graduates, which focused on exchanging ideas on environmental sustainability and ways of improving the quality of research and teaching in higher education.

A magazine article "Malaysia versus Waste"[14] has been written by Dr Kok Siew Ng and Dr Eleni Iacovidou and featured in the IChemE magazine, The Chemical Engineer (TCE), July/August 2020 (949/50), p.30-33.

Acknowledgements to Professor Denny Ng (Heriot-Watt University Malaysia) & Professor Wan Azlina Wan Ab Karim Ghani (Universiti Putra Malaysia) for supporting this initiative, joining the discussions and arrangements for various visits to sites and government departments.

8.2 Thailand

Dr Kok Siew Ng visited Thailand in January 2020 to engage with researchers at Chulalongkorn University, Thailand. The meeting was hosted by Professor Anongnat Somwangthanaroj, the Associate Dean of Research Affairs in the Faculty of Engineering. The meeting aimed to discuss collaboration plans to promote circular economy in Thailand. As a result of the meeting, Professor Anongnat Somwangthanaroj has joined SYNERGORS and CRES as a core member, representing Chulalongkorn University in future initiatives of the global networks.



Research visit to Chulalongkorn University, Thailand.

8.3 Brazil

Municipal solid waste (MSW) is defined as a combination of household waste and urban cleaning waste in Brazil. Recent data showed that the MSW generation per capita in 2019 was 1.04 kg/person/day, an approximately 11% increase compared to the value in 2009[15]. Organic materials are the major component of MSW collected in Brazil (45.3% in 2019). The main inorganic wastes are plastics, followed by paper and cardboard. The MSW collection coverage of Brazil was at 92% in 2019 and approximately 73% of the total municipalities had selective waste collection programmes to increase the recovery of recyclable wastes. Brazil is currently relying on sanitary landfills as the main method of

MSW management and the shift from open dumps to sanitary landfills has been at a very slow pace. The recycling rate reported in 2019 was under 4% with less than 20% of the Brazilian municipalities having recycling programmes. However, Brazil has put an impressive effort into recycling aluminium and the latest figure showed that 97.4% of aluminium cans were recycled in 2020. The municipal government is responsible for collecting household wastes and cleaning public areas by hiring public or private contractors.

The main legislation dealing with the MSW management in Brazil is the National Solid Waste Policy (PNRS in Portuguese) formulated and published in 2010. It is the very first law specifically providing guidelines on MSW management with economic tools through reuse, recycling and energy recovery approaches. One of the specific goals introduced in the PNRS was the abolishment of unregulated, inappropriate final disposal sites such as open dumps by August 2014[16]. However, the deadline was not met and was later postponed till July 2021. The PNRS relies on three major instruments: extended producer responsibility, sectoral agreement and reverse logistics. Reverse logistics has been highly successful through several projects, one of which is the management of empty agricultural packaging. The Campo Limpo System was established with reverse logistic ideology in Sao Paulo to recover these packaging and dispose of them at the correct destination. The report in 2019 showed that approximately 94% of the pesticide packaging in Brazil was correctly sorted through this system. In addition, the PNRS recognises the role of waste pickers as a formal part of the waste management system, which improves the workers' social welfare significantly. In 2020, the Brazilian government proposed a new regulation to further improve the nation's MSW management system named the National Plan for Solid Waste (PLANARES in Portuguese). PLANARES aims to increase financial support for waste management, eradicate unregulated disposal sites, encourage recycling of both inorganic and organic wastes, and support the development of energy from waste facilities. The deadlines for the closure of unregulated and inappropriate disposal sites have been adjusted under this new plan to August 2024 at the latest.

The Brazilian waste management system is ineffective due to several reasons, one of which is the geographical barrier. The Northeast is less developed and policies such as selective collection programmes have not been well implemented due to the lack of information disseminated and hence low citizen participation. Brazil lacks specific targets for MSW management, and laws and regulations have not been strictly enforced. There have also been several attempts to improve MSW management through technologies such as waste-to-energy and incineration, but these projects received strong public opposition. Thus, the Brazilian government will need a stronger education programme on MSW management to gain public trust.

Acknowledgements to Dr Khemmathin Lueangwattanapong for his contribution towards the literature review and this summary, as well as to Prof Francisco Gaudêncio M. Freires (UFBA, Brazil); Dr Jorge Arturo Aburto Anell and Dr Elias Martinez Hernandez (IMP, Mexico); Dr Eleni Iacovidou (Brunel University London, UK) and Dr Long Seng To (Loughborough University, UK) for supporting this initiative and joining the discussions.

8.4 Mexico

Mexico defines municipal solid waste as materials that come from households, restaurants, hospitals, shops, offices, and public spaces. The latest data showed that the MSW generation per capita in 2015 was 1.2 kg/person/day, significantly increased from 0.84 kg/person/day recorded in 1997[17]. This increase was caused by several factors such as urban growth, industrial development, technology advancement and change in consumer behaviour. The majority of the MSW collected was organic materials (53%). The separation of wastes into organic and inorganic fractions was carried out by municipalities. Mexico has high MSW collection coverage (>90%) and approximately 92% of the total municipalities in 2018 had MSW collection services. The door-to-door collection is the main service provided in Mexico. Final disposal to landfill is the key method used to manage MSW in Mexico. It was

reported that about 74% of MSW in 2012 were disposed either to the controlled or sanitary landfills[17]. Despite a low recycling rate (9.6%), Mexico is a leading nation in Latin America with a 57% polyethylene terephthalate (PET) recovery rate in 2019[18]. The waste management system in Mexico is composed of 6 components: MSW generation source, manual and mechanical sweeping, collection, transport and transfer, treatment, and final disposal[19]. Waste collection and transport is managed by local municipalities. Private collection services are responsible for recyclable MSWs, which are originally separated at the sources such as households. The MSW collection system is also driven by informal workers (waste pickers and sorters), who are involved in all stages of MSW management scheme from the generation source to the disposal site.

The main legislation on MSW management in Mexico is the General Law for the Prevention and Integral Management of Wastes (LGPGIR in Spanish), which was published in 2003[20]. The LGPGIR law requires municipal governments to develop and execute programmes for MSW prevention and management. The policy proved to be unsuccessful as only 46 out of 2,269 municipalities created a waste management program. In addition, Mexico does not have a specific national target for MSW management. In 2019, the Secretariat of Environment and Natural Resources (SEMARNAT in Spanish) issued the 'Zero Waste Initiative', shaping the national vision towards sustainable waste management based on the circular economy principle. One of the key goals is to close open dump sites and divert MSW from landfills.

There are several barriers to effective MSW management in Mexico such as a lack of clear targets, low citizen participation, poorly enforced regulation, a lack of market incentives for recyclable materials, and insufficient waste treatment infrastructure and budget. Some of these issues have been addressed with solutions under the new initiative. However, without a clear goal and timeline, the 'Zero Waste Initiative' may not be successfully implemented.

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9. International Knowledge Exchange Platform

cres The Society of Circular, Regenerative and Sustainable Systems

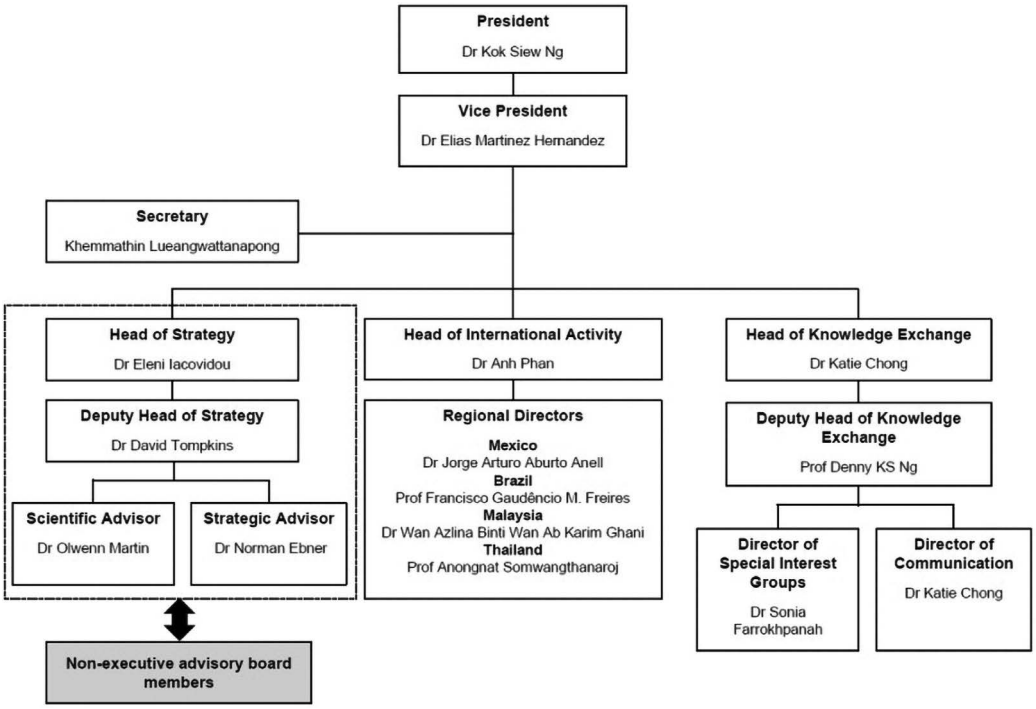
The Society of Circular, Regenerative and Sustainable Systems (CRES) was launched at the University of Oxford on the 3rd of February 2020, with a vision of bringing together academia, industry, government and society in order to integrate systems thinking into everyday decision making. CRES was built upon the UK and international networks developed through the SYNERGORS project consortium.

The core purpose of CRES is to re-invent systems to deliver a sustainable future. CRES focuses its activities on fostering a better understanding of the negative environmental impacts of economic and social systems and promoting the generation of environmental and social net-gains and economic prosperity via innovation and exploration of new technologies, business models, policies and social practices.

Circularity and decarbonisation are at the centre of CRES's work, in areas that include resource management, energy systems, the food-water-energy nexus and urban planning. Other types of systems may also be considered in the future. Longevity, knowledge exchange and impact beyond academic publication will be key aspirations of CRES.

Group Photo from CRES Launch Event at the University of Oxford, Feb 2020

CRES Team Structure



CRES's Mission Statement

The mission of CRES is to create a supporting environment for cross-disciplinary and cross-sectoral activities that promotes the development and implementation of innovative ideas to address complex global issues.

Strategic Objectives

CRES aims to deliver its mission through the following strategic objectives:

1. Create a trans-disciplinary knowledge exchange platform in the area of sustainability to promote collaboration across academia and society and develop innovative ideas to solve complex global issues through communications and events.

2. Identify gaps in knowledge and expertise that are hindering the implementation of sustainable solutions for environmental, societal and economic challenges.

3. Provide education and training to students and practitioners in industry, government and the civil sector to a) Foster leadership in the fields of sustainability, environment and energy and b) Integrate systems thinking into decision-making; while remaining adaptive to respond to emerging demands for new sustainable systems expertise.

4. Provide scientific evidence for strategic direction and solutions for sustainability challenges to policy makers, industry leaders and civil society

Activities Conducted

Webinars: CRES members have organised a number of webinars to promote knowledge exchange and academic discourse between its membership.

1. **A Participatory Approach for Visualising Energy Resilience in Nepal from a Whole**-System Perspective: Dr Katie Chong (Chair), Dr Long Seng To, Dr Louise Reardon, Dr Xinfang Wang, Dr Asha Singh (Speakers)

2. **Plastics: Friend or Foe? Polymers for Monitoring of Environmental Contaminants:** Dr David Tompkins (Chair), Dr Marloes Peeters (Speaker)

3. **A Systems Engineering Approach to the Food-Energy-Water Nexus**: Dr Elias Martinez Hernandez (Chair), Prof Aidong Yang (Speaker)

Blog: CRES has published a wide range of articles on its website, exploring topics of sustainability and environmental challenges. These can be found here: **https://cres-society.org/blog/**

Social Platforms

CRES website: **https://cres-society.org/**

CRES is active on Twitter: **https://twitter.com/cres_society**

CRES's Linkedin Group can be found and joined here: **https://www.linkedin.com/groups/8931083/**

10. Recommendations and Future of SYNERGORS

The SYNERGORS project explored new strategies in promoting resource recovery from secondary organic waste streams including food waste, residual biomass and municipal solid waste. The project led to substantial impacts beyond academia, resulting in 9 academic publications, new experimental studies with Anaero Technology, a number of engagement activities and international visits (including case studies in Malaysia, Brazil and Mexico), and the creation of the Society of Circular, Regenerative and Sustainable Systems (CRES) which aims to promote systems thinking and circular economy.

Key Recommendations

1. Waste and recycling industries should move away from a treatment-oriented waste management approach and adopt a more transformative and innovative resource recovery approach to achieve a more circular economy.

2. A systems approach to addressing waste management is needed to promote collaboration among different groups of stakeholders (e.g. government, local authorities, waste and recycling industries, commercial sector, public etc.)

3. Resources embedded in organic waste streams should be exploited to create value-added products such as chemicals and hydrogen. This requires significant revamping of existing waste treatment facilities. Further research is needed to improve system efficiency and achieve greater cost reduction.

The next phase of SYNERGORS

SYNERGORS members (Prof Aidong Yang, Dr Kok Siew Ng and Dr David Tompkins) will join the new Oxford's AGILE project, funded through the £10 million NERC Changing the Environment programme (2022-2027). The team will examine the regional nutrient flow in the UK by applying systemic innovation concept and provide recommendations to inform policy making at local authority and Defra.

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