STEPS

Sustainable Plastics
and Transition Pathways

ANNUAL REPORT 2022

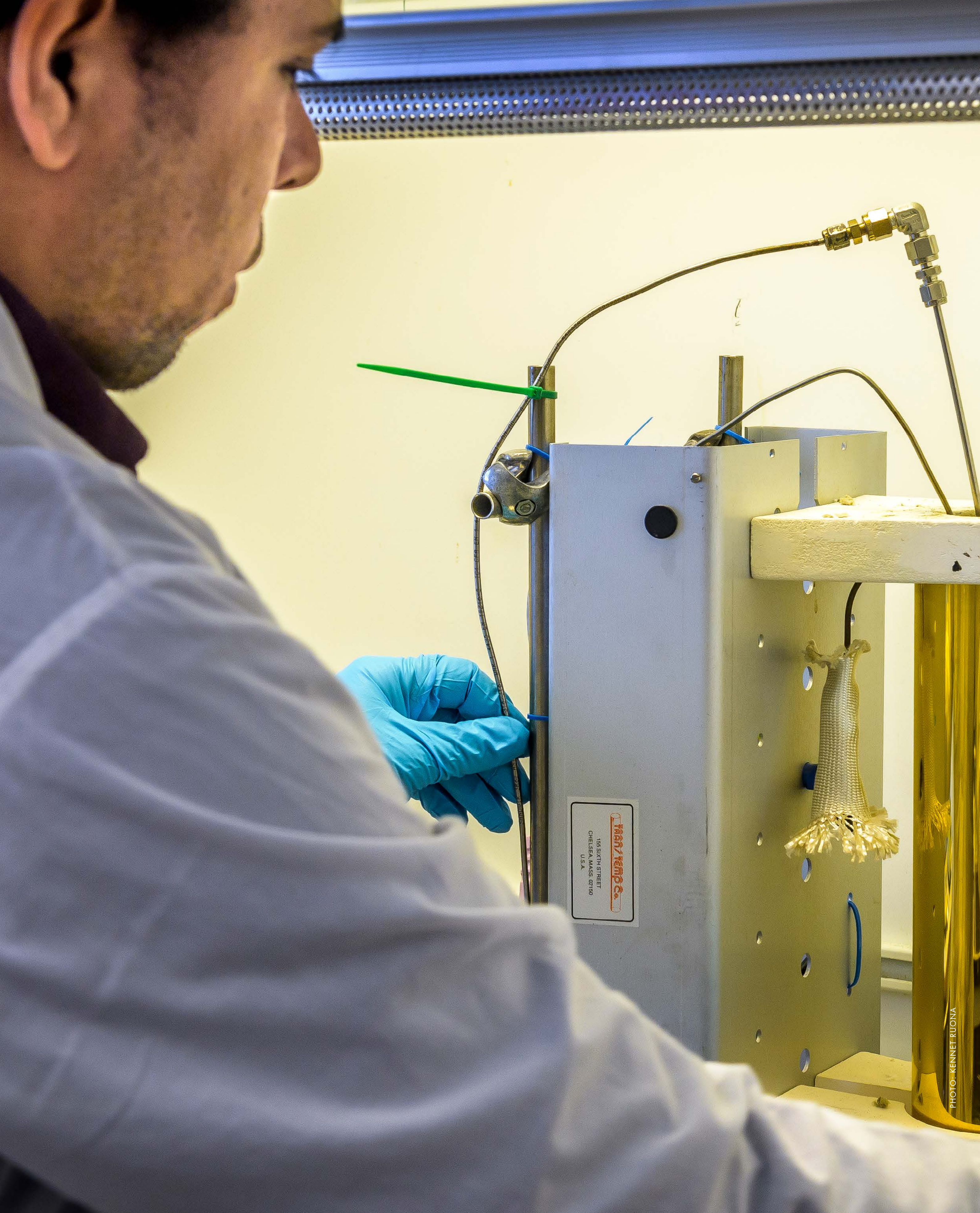


PHOTO: KENNET RUONA

Contents

COVER ILLUSTRATION BY CATRIN JAKOBSSON

STEPS programme meeting at Bäckaskog Castle 2022.

STEPS programme

STEPS research programme was initiated in 2016 with the vision of a future society in which plastics are sustainably developed, produced, used and recycled in a circular economy.

STEPS is based on a close collaboration between academic and industry partners. The consortium includes Lund University, University of Copenhagen, RISE, IVL Swedish Environmental Research Institute, 21 industrial partners and the County Council of Scania.

Our work on transition to sustainable plastics is divided into three research work packages: green building blocks, bio-based polymers, and plastic governance.

During our existence as a programme, we have:

- Designed novel biobased monomers that have been made into polymers.
- Produced two plastic demonstrators: a floor coating and textile fibres with superior qualities and low climate impact.
- Suggested transition pathways towards a sustainable plastic system.

"We believe in strong collaboration between academia and industry at an early stage through which we can ensure that our research corresponds to real societal needs and questions", says Professor Rajni Hatti-Kaul, STEPS Programme Director.

ILLUSTRATION: FRIDA NILSSON

Introduction

2022 was a dramatic year in many respects, characterized by many as a new world disorder but also a year bringing hope. Narrowing the outlook to the focus of STEPS and plastics, there was at least one promising, global event.

In March, the UN Environment Assembly adopted the resolution to end plastic pollution and to create a legally binding global instrument by 2024. "Plastics are fossil fuels in another form", said the UN Secretary-General. An Intergovernmental Negotiating Committee (INC) was formed. The negotiating work was launched last year with sessions in Kenya and Uruguay, the next one is scheduled to be in Paris in May 2023. The treaty should address the entire plastic lifecycle. More sessions are planned and hopefully we will see a draft binding agreement by the end of 2024, to be signed. At the same time STEPS as a Mistra-program will come to an end. Could STEPS contribute to the treaty?

The plastic pollution is by now an accepted fact illustrated in many ways. The digital Archeoplastica museum is created by an Italian in Puglia in southern Italy. From the Adriatic Sea he has collected and displayed more than 500 different articles made of plastics. What is unique is that he has managed to put an approximate date on each artifact showing e.g. that a plastic bottle originates from the 1970s. Plastics will not decay over the decades. His museum is pretty educational and is being exhibited not only by National Geographic but also used in schools and other organisations. But there are areas where plastics are precious and must not decay. Museums are struggling to preserve art made from various plastics. Last year an expert, also called the Queen of Plastics in those circles, published a bestseller, "Properties of Plastics, A Guide for Conservators".

We need a variety of playing fields to tackle the plastic problems and possibilities. Not only museums and research institutions! One platform, often overlooked, is standards which Maria Gustafsson emphasises in an interview to be read in this annual report. Though not legally binding, they contribute to transparency and could move the frontier of knowledge into practical use.

Plastics are nowadays ubiquitous, but it has not always been like that. Think about the movie, "The Graduate". There is a hilarious scene where young Ben, played by Dustin Hoffman, gets some advice about his upcoming career from his future father in law: "I´ve got one word for you kid – Plastics ... There is a great future in plastics". This was in 1967 when plastics production was just a small fraction of what is being produced today, not to mention the forecast for the next couple of decades.

Yes, there is still a great future in plastics, just look at all the innovative results and ideas in STEPS addressing the whole life cycle of plastics. What did we foresee when STEPS was launched in 2016? Mistra was quite open in its call the year before, "A Mistra programme on 'Plastic in a Sustainable Society', is expected to provide theoretical and practical knowledge that can facilitate a switch to the use of renewable resources. Moreover, the programme is also expected to contribute knowledge of consumption, reuse and recycling of plastic." Less than two years from now we will sum up what STEPS has accomplished since 2016. The legacies of STEPS will be appreciated, used, and spread. STEPS research and all the valuable ideas yet to be pursued will presumably be continued, preferably in a seamless way. The world is following STEPS with high expectations!

Message from Management

Returning to normalcy in 2022 after two years of the Covid 19 pandemic was a welcome relief. For several STEPS partners it meant meeting in person for the first time after two years of online meetings since the start of the second phase of the programme. The spring programme meeting, in the beautiful surroundings of Bäckaskog castle, thus presented a great opportunity for face-to-face discussions and activities.

With increasing interest in Sweden and the European Union on sustainable plastic use and circular economy, and the negotiations for a global plastics treaty, we believe that STEPS´ three-pronged research strategy of developing biobased plastics, design of plastics for enhanced recyclability, and plastic governance for transition to a sustainable plastic system, is sound. STEPS researchers are now increasingly invited to many of the important conferences and other national and international plastic related events e.g. in Almedalen, Swedish Environmental Protection Agency's Plastdag, and expert meetings with the European Environment Agency, to name a few activities this past year.

On the academic front, one of our doctoral students in work package two, focusing on biobased polymers, defended his thesis on biobased polyesters and polyurethanes, and several other doctoral students have been getting ready to defend their theses during 2023. There is also a marked increase in the number of publications produced by the programme in scientific journals. One previous STEPS article, "Designing biobased recyclable polymers for plastics," published in a highly ranked journal, *Trends in Biotechnology*, has been listed among the 25 most cited articles in the journal since 2020, a testimony to the growing impact of our research. The 2022 paper on plastics and climate change published by STEPS researchers in work package three which focuses on plastic governance is also attracting great interest. It brings to light the complexity of the current plastic system, requiring integrated solutions that are beyond managing plastic litter and single use plastics. Decarbonisation of the plastic industry is an issue that our management group colleague, Lars J Nilsson, brings forward in one of the IPCC sixth assessment reports, on climate mitigation, where he is the lead author for a chapter on industry.

Since we started the second phase of the programme, the focus in STEPS has moved towards upscaling of building blocks and polymers for technical evaluations as well as economic and environmental assessments. Some of the management group members have been instrumental in identifying the candidates for scale up, while the STEPS Board has been generous to support these efforts with the strategic reserve funds. Plastic recycling is another research activity that is taking shape within STEPS. These changes reflect our programme's desire to make a sustained, practical impact with our research, and to test results and processes together with industry. Our aim is to develop some more demos and applications before the programme ends in 2024.

Rajni Hatti-Kaul
PHOTO: KENNET RUONA

PHOTO: SHUTTERSTOCK

Three work packages

Green Building Blocks: Work Package One

WP1 has focus on production of polyester building blocks from surplus renewable feedstocks using clean and cost-effective process technologies.

In 2022, STEPS researchers developed efficient lab scale microbial processes for the production and recovery of pure biobased building blocks, namely adipic acid and FDCA (2,5-furan dicarboxylic acid). Furthermore, four novel furan derivatives were synthesized, one of which was tested for polymer synthesis with WP2. Work on scaling up of 5-HMF production from fructose beyond lab scale was also initiated. Monoaromatic compounds were produced from technical softwood Kraft lignin, i.e., LignoBoost™ and tested by WP2 to obtain a vanillin-based bisphenol under mild conditions. An approach for temperature-induced acetone–water fractionation was also developed to refine the properties of LignoBoost™ lignin, generating fractions suitable for value-added applications.

Finally, work on the chemical recycling of plastic waste, involving techno-economic aspects and integration opportunities, was initiated. Removal of chlorine and nitrogen-containing compounds during thermal recycling of consumer waste plastics was studied. Two adsorbents for removing bulky organochlorides have been developed that proved to be superior to existing, commercial options. Even enzyme catalyzed degradation of two commercially available polyesters, PET and PBAT (polybutylene adipate terephthalate), was studied. Furthermore, a downstream process for separation of monomers from the degraded PBAT, and their purification for further upcycling, was developed.

Biobased building blocks and upscaling: Work Package Two

WP2 investigates polymerisation, processing and characterisation of bio- based plastics using potentially the building blocks from WP1 and other sources toward applications such as fibers, coatings, packaging and oral hygiene products. Particular attention is paid to


PHOTO: KENNET TUONA

replace non-recyclable thermosets with potentially recyclable thermoplastics.

In 2022, STEPS researchers continued their investigations on the design and synthesis of new biobased polyesters and polyurethanes in lab scale. Particularly, they have been focusing on the chemical recycling aspects of acetal-containing polyesters and polyurethanes. The PhD student, Niklas Warlin, has defended his thesis. WP2 has also deepened collaboration with WP3 in terms of preliminary Life Cycle Assessments (LCA) of not only monomer structures but also polymerisation processes. The researchers have chosen a methyl paraben-based monomer to initiate upscaling investigations and have produced two kg of the monomer that will be used for kg scale polycondensation by Clariant in 2023. This will be relevant for Mission 3. Researchers have also fulfilled the task in Mission 1 about developing and validating oxygen barrier property tests at Tetra Pak in small scale.

Plastic Governance: Work Package Three

WP3 has the main task to assess potential transition pathways to develop research-based advice on policy and industrial strategies for sustainability in the longer term. Governance and policy implications for a circular plastics economy are addressed, including social dimensions and the roles and responsibilities of key actors.

In 2022, papers focused on various aspects related to the governance of plastic, outlining the feasibility of different pathways, the use of narratives in the European Plastics Strategy, and ways of breaking lock-in situations. More conceptually-oriented papers focused on the transformative potential of changing the scalar organisation of waste governance, and the various types of contestations identifiable in transition processes. These contributions highlight how the transition require specific policy attention to the characteristics of the different niche innovations that may be part of a future sustainable plastics system, since they have vastly different preconditions for scaling up. WP3 research was also focused on life cycle assessment in relation to biobased biodegradable plastics and closed-loop recycling practices.


PHOTO: ISTOCK

STEPS Missions

STEPS missions aim at intensifying the collaboration between industrial, regional and research partners by co-developing and evaluating carbon-neutral plastic products for specific target applications. Missions are formed for developing better products, identifying challenges for transition, and to suggest potential pathways for circular economy and reduced plastics pollution.

Mission 1: Biobased plastics for packaging applications: Level of food protection vs ease to recycle

Mission leader: Tetra Pak. Other STEPS stakeholders involved: GPS, Lund University, Nordic Sugar, Orkla Foods.

The mission was ended during the year, and communicated through the dissemination of two scientific articles; **Exploring the industrial perspective on biobased plastics in food packaging applications–Insights from Sweden** (K Molina-Besch, H Keszleri, Sustainable Production and Consumption, 2023) and **Use phase and end-of-life modeling of biobased biodegradable plastics in life cycle assessment: A review** (K Molina-Besch, Clean Technologies and Environmental Policy, 2022).

Mission 2: Biobased textile fiber

Mission leader: RISE, IKEA. Other STEPS stakeholders involved: Clariant, GPS, Ludvig Svensson, Lund University.

Research work continued on the synthesis of Polyester polytrimethylene furandicarboxylate) (PTF) from biobased 2,5-furandicarboxylic acid (FDCA) and 1,3-propanediol. The main aim this year was to improve the flexibility of PTF as a suitable material for fiber application. In addition, inducing of the third monomer into a PTF chain in order to increase its flexibility and processability was tried. The attempt of using low molecular weight of bio-PTF was also discussed with IKEA. One possible application of such low molecular weight of PTF is to produce nonwoven fabric by melt blowing. In addition, the inducing of the third bio-monomer into PTF chain in order to increase its flexibility and processability was tried.

Mission 3: Biobased toothpick

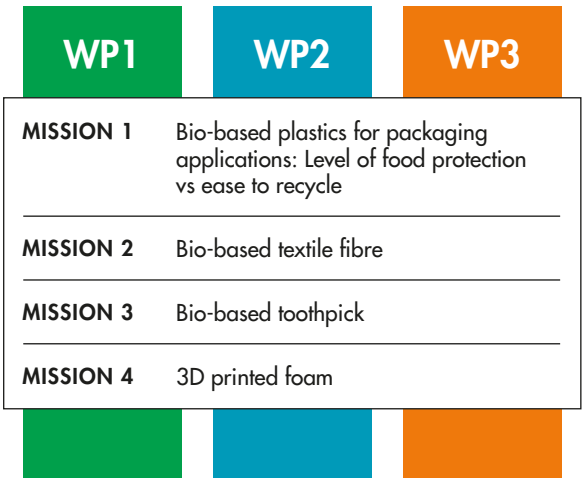
Mission leader: TePe. Other STEPS stakeholders involved: Clariant, Lund University, Nordic Sugar.

A series of AB-type polyesters have been synthesized in lab scale in work package two, which showed desirable thermal properties and promising potential for further optimization and upscaling investigations toward TePe's toothpick applications. Two kg of a selected monomer based on methyl paraben was produced by Ramidus AB and was delivered to Clariant AB for kg scale polymerization investigations.

Mission 4: 3D printed foam

Mission leader: Jonas Ihreborn AB. Other STEPS stakeholders involved: Lund University, Nordic Sugar.

Samples using different materials and morphologies showcasing their structural properties have been produced and measured during the year, with results presented at the NordDesign conference and in a project report by Florian Ventur. Fused deposition modeling has also been evaluated and has resulted in one Master's thesis by Samuel Bengtsson.



A chat with researchers and board members in STEPS consortium

Smita Mankar's thesis contributes with important knowledge on biobased polyesters

Smita Mankar's thesis focused on producing biobased building blocks that can enhance the thermal, mechanical and barrier properties of bio-based polyesters. She has also studied new recycling strategies for biobased plastics by using chemicals or enzymes. These strategies may shed some light on the design of recyclable biobased plastics.

In her research, she is motivated by knowing that she can contribute to the sustainability of the future of plastics. Another important thing is that she gets to test her own ideas to figure out if they will work.

She defended her thesis in February 2023 within STEPS work package two: biobased polymers and upscaling. She was based at the Centre for Analysis and Synthesis, Department of Chemistry, Lund University.

What was your research about?

Plastics are widely used every day, in our clothes, lunch boxes, mobile phones and in many other things. But their large production from non-renewable fossil resources, and limited recycling methods is an issue.

In my thesis, I have made very interesting biobased building blocks and used them to make biobased plastics. I have also studied new recycling strategies for biobased plastics by using chemicals or enzymes. These strategies may shed some light on the design of recyclable biobased plastics.

What are the main findings?

My findings include the following:

- Newly synthesised biobased building blocks can enhance the thermal, mechanical and barrier properties of biobased polyesters.
- The use of vanillin and other biobased building blocks can effectively reduce greenhouse gas emissions.
- Recycling loops can be improved by designing monomers with cleavable structures.
- Polyesters with vanillin-based structures can be enzymatically degraded.
- Aliphatic polyesters with rigid units can combine excellent thermal properties and biodegradability.

Smita Mankar. PHOTO: KENNET RUONA

Did anything surprise you during your work?

The chemical structures of building blocks are very important. If we are introducing new structures, they should impart some amazing properties to the plastic. In my work, I also studied chemical recycling of plastics. Interestingly, I found that the recycling loop can be made shorter by breaking only a few bonds in the plastic during recycling. We can use these recycled products for making the same polymers with a less energy consuming process.

How does your work relate to other research on plastics?

Currently biobased monomers are being researched very intensively. But we should not aim to only make new monomers and new plastics. Recycling, biodegradability and greenhouse gas emissions should be included from the start when you develop new polymers in the laboratory. This is what I have done in my research.

How can your research be used by stakeholders?

I made different types of building blocks for polyesters. Some polyesters have properties that make them suitable to make them into chemically recyclable fibres for clothing.

Some polyesters are good to use for packaging purposes, as they have good barrier performance, transparency and heat resistance up to 105 degree (glass transition temperature, which is the temperature at which 30–50 carbon chains start to move) which is currently what everyone is looking for in plastics.

What are your views on the plastic system?

Currently, we are still using plastics (99 percent) that are made from fossil resources. This is definitely not sustainable.

To make plastics more sustainable, various strategies have been implemented /policies have been made. In my point of view, we should follow the three R:s; Reduce, Reuse and Recycle. Use less plastics, use recyclable plastics, and use biomass resources for making transitions toward sustainable plastics.

In packaging, sometimes various layers are used for improving barrier for moisture, oxygen, etc. However, recycling of such types can sometimes be difficult. I wonder if we can we make plastics for packaging which will not need many layers and will be easily recyclable.

What drives you as a researcher?

Knowing that I can contribute to the sustainability of the future of plastics makes me very happy. Another important thing is that I get to collaborate with researchers in different areas. I also get to work on my ideas/strategies and if it doesn't work out, I get to know why it didn't work out by doing experiments on my own.

▶ Smita Mankars thesis is entitled: **Toward Biomass-Derived Recyclable Polyesters**.

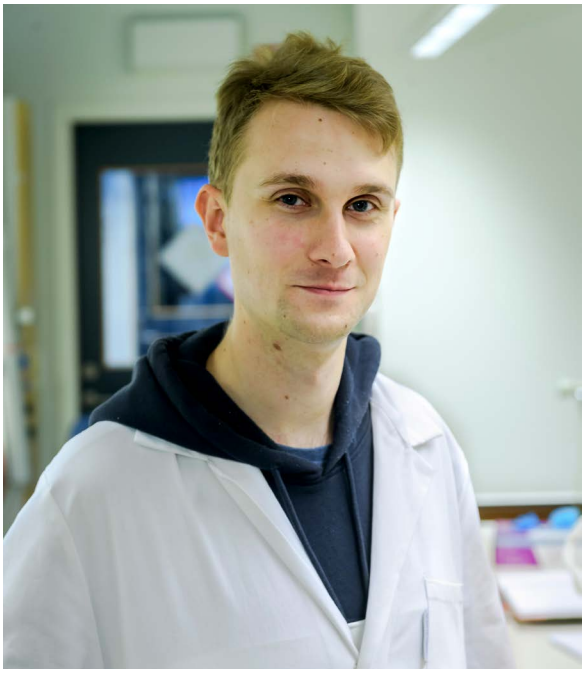
Niklas Warlin's thesis contributes with important knowledge on molecular design, synthesis and characterisation of bio-based polymers

Niklas Warlin defended his thesis in spring 2022. The main focus of his research is molecular design, synthesis and characterization of bio-based polyesters and polyurethanes - aiming to achieve sustainable materials with enhanced thermal stability, chemical recyclability, and low carbon footprint. In his research, he gets motivated both by greater things, like trying to solve existential crises like global warming or the plastic pollution problem, but also by the smaller things, like day-to-day successes in the laboratory.

He completed his PhD within STEPS work package two: biobased polymers and upscaling. He was based at the Centre for Analysis and Synthesis, Department of Chemistry, Lund University.

What are the main findings?

Since my thesis is divided into five chapters, depending on my five papers, I will try to summarise the findings in five parts: Paper 1: I developed a synthesis procedure for a new rigid bio-based monomer and demonstrated that it can be used for polyester and polyurethane synthesis. Interestingly, this monomer is more suitable for polyurethane synthesis due to thermal stability issues at the high temperatures required for polyesters. Paper 2: I synthesised another bio-based monomer and used it for polyurethane synthesis. These polyurethanes could be spun into fibers, and chemically recycled in the presence of acid. Paper 3: A new efficient method for synthesising 5-hydroxymethylfurfural was developed. Interestingly, a biphasic system of water and the green solvent dimethylcarbonate resulted in very high conversion and yields. Paper 4: Several new monomers were synthesised using lignin-based phenols and sugar-based furans. The monomers were suitable for polyurethane synthesis and could be reversibly crosslinked by the Diels-Alder reaction to improve their mechanical and thermal properties. Paper 5: A new type of acetal monomer was synthesized from lignin-based phenols and used to synthesize polyesters. These polyesters could also be chemically recycled but required harsher conditions (as compared to paper 2) due to the different type of acetal bond.



Niklas Warlin. PHOTO: KENNET RUONA

Did anything surprise you about your work?

Many things! One thing that stands out is the thermal stability of furans. In the early stages of my PhD studies, I was surprised by how sensitive many furans tend to be towards high temperatures. Especially considering that furandicarboxylic acid can be used for synthesizing PEF, which requires a reaction temperature of at least 220 °C. Later, I learned that the electron density on the furan ring is extremely crucial for the thermal stability, and the reason furandicarboxylic acid can be used to synthesize PEF at 250 °C is due to the two electrons withdrawing carboxylic acid groups, thus deactivating the furan.

How does your work relate to the research on plastics?

My research focuses on design of biobased monomers and polymers with low carbon footprint, enhanced mechanical and thermal properties, that can be recycled by different methods. Carbohydrates and lignin have been identified as important sources of renewable starting materials which is why I have tried to valorise these sources in particular. The reason I try to make the polymers, polyesters and polyurethanes, are that they constitute a significant portion of industrial plastics (~6-8 % each of the total global production of polymers) and we have many partners who are interested in these polymers. Our partners also have a lot of expertise in these fields of course. There are other types of polymers which could be made from my monomers (e.g. polycarbonates, polyamides, epoxies) and these polymers would certainly be interesting to study, for other researchers.

How can your research be of relevance to other stakeholders?

I believe one of the major findings was how different furans are affected by high temperatures. This may be used by stakeholders to identify what groups of polymers should be targeted depending on what starting material/molecules they are selling. An example from my thesis is the monomer in my first paper. I struggled for two years to make polyesters from it but never really achieved good results. After less than six months of working with polyurethanes, I made polymers with far better properties than the polyesters. I therefore believe polyurethanes are more likely to reach quick commercial success than polyesters if you sell furans. Aside from this, I have also made many interesting monomers (one was used in the demo-product, StepOn) which might be scaled up further, to reach pilot scale production of polymers.

In terms of societal impact and outreach activities: I have personally supervised six project and master students, been a lab/exercise teacher for hundreds of engineering students, held several popular scientific lectures for students ranging from 10-18 years, attended and presented at three conferences, and been interviewed by a podcast.

What are your views on the plastic system?

Plastics are an essential group of materials for society, which is demonstrated by the fact that there are polymers in virtually all things that can be bought. The environmental problems with plastics stem from how they are used, and especially how they are disposed of. With an educated population (who collects used plastic products instead of throwing them away) and efficient recycling practices, most of the environmental issues caused by plastic consumption could be resolved.

What drives you as a researcher?

I am motivated both by greater things like trying to solve existential crises like global warming or the plastic pollution problem, but also by smaller things, like day-to-day successes in the laboratory. For example, by successfully synthesising a new molecule, publishing a paper, or helping a student understand a chemical reaction. I believe both parts are equally necessary for me to function as a scientist. Without a grand goal my work would feel excruciatingly pointless, and without small day-to-day victories my work would be painfully boring.

▶ Niklas Warlin's thesis is entitled: **Towards sugar- and lignin-based polyesters and polyurethanes with enhanced properties**.

Stine Madsen's research questions at what level transformational change should be implemented

Stine Madsen's thesis shines light on frictions and power imbalances as EU waste directives are implemented in Danish law. "Sustainable transitions are all about changing systems. My research questions are related to at what level decision making should happen."

Stine Madsen's thesis, which she defended at the Department of Human Geography at Lund University, explores how Denmark has reacted to the 2018 revisions of European Union waste directives. The directives introduced a set of priorities for the efficient use of resources, and greater application of the waste hierarchy in attempts to ensure that waste is first reduced, then reused, recycled, incinerated, and as a last resort, landfilled. In 2020, in response to the directive, the Danish state removed decision making powers from the municipal level, and set a cap on incineration. Another change is that all 98 municipalities have now to use the same system to collect waste.

She explains that these attempts to pursue a circular economy in the Danish waste sector have been highly contested. Actors with stakes in the system are mobilising to try to shape the unfolding changes: some actors work to defend the current system, characterised in Denmark by a relatively high level of incineration, other actors align with the promotion of greater

Stine Madsen.

recycling. Several actors want to see changes that are more radical, and in turn promote increased reuse and reduced consumption.

– Studying how Denmark is now implementing EU policies into national law is interesting. It points to challenges of how to plan and implement transformational change in national systems that might differ from each other. How could, and should, nation states translate EU policy across governance levels, and engage actors in the process? says Stine Madsen.

Transformational change at the right level

Based on her thesis results, one of Stine Madsen's conclusions, is that it is important to problematise assumptions relating to at what level decision making should happen when EU policy is made into law. This is an important finding, according to her, since scholars are currently making strong arguments in favor of pursuing systemic change at the regional or municipal level – based on subsidiary arguments that the subnational can more effectively translate the direction of change decided at higher levels of governance into local industrial opportunities.

– My research suggests that delegating decision powers to the local or regional level is no panacea for effective governance. Rather, in Denmark, it seems that decades of strong municipal power in the waste sector, is part of what explains the country's high level of incineration, which meets critique from the perspective of circular economy.

Instead, Stine Madsen argues that a shift towards circularity requires a range of different pathways and policy support - that should be designed with more concern for historical and contextual settings. Aspects such as power imbalances, friction, and analysis of where opportunities for change are the greatest, are also important.

She gives an example:

– I studied two niche alternatives to the management of plastic packaging: reuse and chemical recycling. We found that chemical recycling actors in the Danish setting have access to resources and networks of powerful allies such as the petrochemical industry, while resources and networks are significantly scarcer amongst reuse actors. These niches are therefore likely to require vastly different policy support to be institutionalised further, and become viable alternatives to incineration.

What form this support could take practically depends on how Denmark decides to allocate resources, and decision powers in the future, according to Stine Madsen. But it is crucial that Denmark as a state takes ownership of the transition to a circular economy.

– When it comes to waste, however, this is a highly regulated and institutionalised system, which for decades has been governed by changing rationalities – it has not been allowed to run its own course. There is a need to dismantle unsustainable institutions in the system, and attempts to move beyond certain single use products can be seen as an example of this. The state also needs to be proactive in supporting a milieu where the playing field between actors is more even, says Stine Madsen.

▶ Stine Madsen defended her thesis in early 2023, within STEPS work package three: plastic governance. The thesis is entitled: **Pursuing a Circular Economy in the Danish Waste Sector: Scale and Transition Dynamics in Transformative Innovation Policy**.

Oliver Englund's thesis identifies biotechnological pathways towards more diverse biobased building blocks

Oliver Englund Örn defended his thesis in February 2023, within STEPS work package one: green building blocks. He was based at Biotechnology, Department of Chemistry, Lund University. In this interview, he highlights his main findings, and how his research can be used by other researchers and stakeholders. In his research, he gets motivated by curiosity and a desire to develop.

What was your research about?

I performed my PhD in biotechnology focusing on microbial production of biobased plastic building blocks.

Specifically, I used *Escherichia coli* bacterial cells, and genetically modified them to produce aromatic and aliphatic plastic building blocks from glucose. These building blocks, or monomers, can be used to develop plastic polymers, once you recover them in a pure form from the concoction they have been

Oliver Englund Örn.

produced in. I also produced the aliphatic building blocks adipic acid and 4-hydroxybutyrate form biobased 1,6-hexanediol and 1,4-butanediol, respectively, with the bacteria *Gluconobacter oxydans*. The same techniques I used can also be used to produce many other chemicals.

Using bacteria such as *E. coli* has many benefits. If you compare the process of making biobased monomers directly from sugar, you can get a HMF-molecule (5-Hydroxymethylfurfural) by a chemical process which is good, but with *E. coli* or other bacteria, you can change the metabolic pathway and produce a more diverse range of plastic monomers from different sugars with different efficiencies. This is also why biotechnology is such a growing area.

What are the main findings?

I could produce both protocatechuic acid and adipic acid from biobased substrates such as glucose to be among of the highest achieved concentrations reported in scientific literature. I have also worked on enzymatically degraded PBAT (polybutylene adipate terephthalate), and used similar techniques to convert the degradation products to value-added chemicals.

Did anything surprise you during your work?

Learning about the state of the plastic industry and recycling was an eye opener in many ways.

How can your research be used by stakeholders?

The aim was to provide biomass producers a way to transform their biomass, for example glucose, into plastic building blocks. Therefore, those who have available biomass or production plants to transform the biomass could benefit.

My research can also be used by other researchers who work to develop this field. Since the thesis presents similar results to other research using *E. coli*, it shows that the process for transforming bacteria to monomers is replicable.

Could these research results be scaled up and become a viable biobased plastics alternative?

Well, there is certainly enough research to show that this process works, and that we can produce biobased plastics that are easy to reuse or biodegrade. The main reason that it has not caught on is that it is still too expensive a process in comparison to using oil to produce plastics.

My aim as a researcher is to provide a means for the plastic industry to change, if only in a small way. But to realise that change with the current economic and political drivers I think will be hard. Yet, I do hope that more actors will see the value of investing in more sustainable techniques in the future, in spite of costs. As the research to use second generation biomass from e.g. the forest industry, develops, so can this process catch on too, and become further developed.

What drives you as a researcher?

Curiosity and a desire to develop. I also wanted to do something I could be proud of, and which could be of benefit to others, which was one of the reasons this PhD project attracted me from the start.

▶ Oliver Englunds thesis is entitled: **Towards sustainable plastics: Microbial production of aromatic and aliphatic building blocks from biobased feedstock and plastic hydrolysate**.

Lars J Nilsson sees similarities between STEPS work and the solutions put forward in the IPCC sixth assessment report

Professor Lars J Nilsson has been involved in STEPS since the very start. He is especially proud of the fact that the programme connects plastics to climate change, and highlights the need for multiple and integrated pathways to change the plastic system – in a time when most of society's focus is still on plastic litter and single use plastics.

– Throughout, we have tried to emphasise the bigger picture in our work. Plastics have to be viewed as a complex system, requiring integrated solutions such as smart use, circular systems and renewable sources. There are no silver bullets or one-size fits all solutions, says Lars J Nilsson, professor at Environment and Energy systems at LTH, and leader of STEPS work package three: plastic governance.

Lars J Nilsson. PHOTO: KENNET RUONA

He reflects that there are many similarities between the ideas and solutions identified in STEPS, and those put forward in the lPCC sixth assessment report on climate mitigation, which was published over the course of 2022. Lars J Nilsson was coordinating lead author for chapter 11: Industry, which focuses on decarbonisation of emission intensive industries including petrochemicals and plastics. Options discussed in the report include reduced demand, improving material efficiency and circularity, electrification and hydrogen, sourcing of non-fossil carbon, and carbon capture and storage solutions.

– These ideas should be of crucial interest to the plastics industry, especially since the sector is a major contributor towards emissions. However, compared to other industrial subsectors the plastics industry appears to be the least ambitious or progressive on decarbonisation, says Lars J Nilsson.

Decarbonising industries will be hard but not impossible, according to Lars J Nilsson. One hurdle is the lack of experience, and of large scale implemented research solutions. He compares it to renewable energy, where efforts to devise sustainable alternatives to fossil-based energy sources have been ongoing for more than 40 years. However, a big advantage is that society's technical know-how, and awareness of the climate crisis, are growing year by year – and that solutions can now be scaled up and implemented at a faster rate than some decades ago.

– I strongly believe that we are seeing something of a mindshift across many sectors. Policies on different levels, public opinion and industry initiatives are all pushing towards more sustainable use of plastics and other materials. In ten years, when society has had time to test and roll out different solutions, we will hopefully see substantial changes in how plastics are used and produced.

A major driver of this sea change will be the expansion of fossil free energy, a development which is set to accelerate as renewable energy is becoming cheaper. Without fossil feedstock for the chemical industry the necessary carbon must be sourced elsewhere. Biobased plastic is only one of many options according to Lars J Nilsson.

– Whether it wants to or not, the plastics sector will have to explore different sources for carbon atoms. This is an exciting development, and one in which STEPS can contribute with important research results. We have already done work on how to produce plastics from carbon dioxide, and are now continuing with a master thesis on how the shift from black to green carbon could look like.

In a shorter perspective, there are two things he would like to see to speed up the transition towards more sustainable plastics use: a carbon price on plastic feedstock to decrease the use of fossil-based resources, and an EU-wide strategy to reduce and improve the use of plastics, across a range of sectors such as food, retail, automotive and construction.

– We use way too much plastic packaging. This type of plastic has a very short life span, and could be replaced by other materials, or reused in different ways. Plastics often look better than metal and glass in comparative life-cycle analyses since it is light weight. This will change as competing materials and goods transport decarbonize, says Lars J Nilsson.

"The process of developing a new standard is very important, and the understandings reached can often be carried over in other fora"

Maria Gustafsson, project manager at the Swedish Institute for Standards, SIS, was asked to join STEPS board when the program started in 2016. She was happy to accept, since she believes that actors from different sectors and fields in society, not least standardisation and academia, should collaborate more closely to take steps leading to sustainable development.

– The Mistra research programmes can take big steps since they run over many years on a large budget and gather both researchers and industry. This is something very positive, says Maria Gustafsson.

Her work at SIS enables her to give important inputs to STEPS' work in relation to how international standards can shape the plastic system.

She explains that standards are of crucial importance to ensure streamlining and implementation of new practices. They serve as strategic tools to enable business to operate efficiently, increase productivity, and access new markets. Standards also help companies develop products that can be used, disposed, and recycled

Maria Gustafsson.

in a similar fashion. As such, they are important to accelerate sustainable change and transformation.

Standardisation related to plastics has been ongoing for many years and covers a wide range of topics such as material quality and durability, biodegradability, and recycling. Sweden is very active in this work; SIS has just now taken over the leadership of the European technical committee on Plastics and has led the international work related to mechanical recycling of plastics for several years.

Another important area for STEPS, and the reason Maria Gustafsson was asked to join STEPS board, is that the European Committee develops standards for biobased products. This work includes standards on terminology, biobased content, sustainability criteria, life cycle assessments, LCA, and communication. For the last year, she and a Swedish convenor have been leading the work to develop a European standard on how to compare biobased products with fossil-based products when doing LCA.

She explains that current methodology disadvantages biobased materials and products in a number of ways, which was highlighted first by European Bioplastics and later the entire Bioeconomy Alliance. She highlights the example that even if the forestry or crop cultivation has rendered a net carbon sink, this is not included in the calculation as biomass feedstock is at best counted as zero. There are also much more stringent requirements put on the biobased value chain when it comes to issues such as traceability and data quality.

– These and several other issues create an unlevel playing field, which becomes even more problematic when you consider that in many cases the actors within the biobased industries are much smaller than the traditional, fossil-based industries. One important part of standardisation is to try to mitigate these kinds of gaps.

While standards are voluntary in nature, unless they are referred to in legislation in a way that makes them binding, Maria Gustafsson strongly believes that this standard can play a crucial role in supporting e.g. companies and policymakers to make more informed choices in connection to the use of feedstock.

– I feel that part of the gain of developing a new standard is the fact that you get people to talk to each other. The process itself is very important and the understandings reached can often be carried over in other fora as well. Another aspect is that many companies want to make a positive change and see the value of being able to communicate to consumers and other customers about it. Here standards can be a useful tool.

What changes does she hope to see in the future in relation to plastics?

– Well, we have to realise that there is no silver bullet solution. Instead, there will be many different solutions that will have to be developed one step at a time. If we wait for a material or technique that is perfect from the beginning and that will solve all problems, we will keep on waiting and not achieve any change at all.

– What is important is to keep an open mind and to try many things at once. This is one of the benefits of the STEPS programme, that different pathways are investigated and developed side by side with research topics such as consumer and industry behaviour, which we need to understand better to achieve lasting change, says Maria Gustafsson.

"In the future, sustainability criteria for plastics will be underpinned by both climate and biodiversity considerations"

Legislation concerning plastics is becoming increasingly more complex with changes on a global, as well as on an EU and Swedish level. A researcher who has been following developments for a long time, and now works within STEPS work package three: plastic governance, is doctor of law Åsa Romson. As the previous Swedish climate and environment minister, and former spokesperson for the Green Party, she has first-hand knowledge of the challenges connected to making a sustainable transition.

– In European society we are just in the beginning of our journey to regulate plastics. On the one hand, we have very far to go when it comes to changing the way we produce and use plastics and increase plastic recycling. On the other hand, there have been huge steps made in relation to single use plastics in the last five years, says Åsa Romson, researcher at IVL, Svenska Miljöinstitutet, and member of STEPS work package three.

Reflecting on the years that have passed, she emphasises the importance of viewing plastics as a system. All aspects of the

plastic value chain need to be reviewed to really get to the root of the unsustainable use of the material, including impacts not just on the climate, but also on biodiversity.

– There are many environmental needs to take into consideration, and they are becoming more complex. In the future, sustainability criteria for plastics need to become broader to include factors such as resource efficiency and impacts on habitats and species.

Going forward, she would like to see more focus on reuse of plastics, while at the same time implementing regulation connected to plastic production. Reuse is extremely effective in reducing environmental impacts. Much focus today is on recycling where new regulation is under implementation.

She is glad new regulation on packaging waste was passed into Swedish law in 2022. It could be an incentive to increase recycling rates, and make plastic packaging more sustainable. The regulations stipulate that all producers of packaging are responsible for collection and treatment of packaging waste and now this regulation has been updated to better integrate the new EU waste and packaging regulations. Another change is that municipalities will now take over the responsibility of collecting consumer packaging, which means that they can debit the producer responsibility organisations. New price categories will also be implemented, with a lower tariff for packaging that is lighter, and easier to dispose of or recycle.

– It will be interesting to see the effects of these new regulations, and if they can drive the design of more sustainable packaging. Will they in themselves be enough to make companies radically review the way they package goods? It is also a question of costs, and how much of additional costs will be transferred onto the consumers.

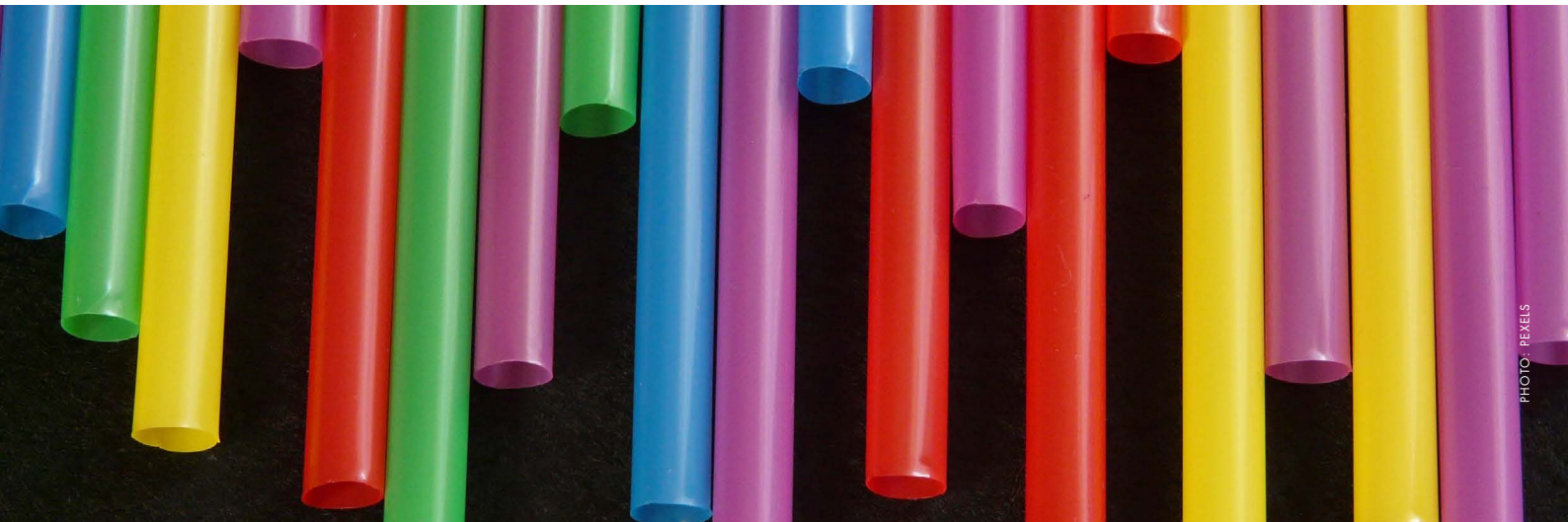
Åsa Romson is also following developments within international standardisation with great interest. Work is currently under way to develop a new standard related to the definition of recycled plastics. In 2022, the European Commission submitted a request for such an international standard to the European Committee for Standardisation.

Åsa Romson.

– It is important that not only the industry, but also the authorities and civil society are involved in how we define recycled plastics. Otherwise, there are great risks for greenwashing, if different actors communicate differently.

Overall, Åsa Romson is positive about the future. She is also pragmatic; and motivated to work on a material that is so integral to modern life, and also used in every societal sector.

– We are currently in a transition, not only related to plastics, but to the survival of our planet. What we do in the next couple of years will decide our descendants' future. That is daunting but also very exciting and challenging. It is great to see so many things happening at the same time, not least the upcoming legally binding UN Treaty to end plastic pollution, and a growing consumer awareness on material use, says Åsa Romson.



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The Year That Passed ...

January

- Meeting with Light My Fire.

March

- STEPS Board Meeting in Mistra's office in Stockholm.

April

- Internal STEPS seminar on plastic additives with SPIF, Clariant.

May/June

- STEPS programme meeting in May-June at Bäckaskog Castle.
- STEPS Director, Rajni Hatti-Kaul, presents on biopolymers for Tetra Pak.

June

- STEPS workshop on bioproducts.

July

- STEPS at Almedalen: **Är mindre plaster lösningen?** Panel talk organised by Mistra with different researchers, including STEPS PhD student Karl Holmberg.

August

- Professor Lars J Nilsson presents key findings from the IPCC report, including industrial sustainable transformation for the Swedish ambassador to South Korea.

September

- STEPS PhD student Karl Holmberg presents STEPS at Naturvårdsverkets Plastdagen, a plastic conference in Stockholm.

October

- Press release issued to Swedish media: **Stuck in plastics: carbon lock-ins make the transition difficult**.
- STEPS programme meeting at Kulturen. Focus on: Plastics in Textiles.

November

- STEPS site-visit at Bi-Qem.

December

- Press release issued to Swedish media: **The most important factors for increasing the use of biobased plastics in food packaging**.

Communication and impact

Making societal, policy and environmental impacts beyond academia are important aspects of the research performed in the STEPS programme. Our researchers are engaged in different activities to highlight our research, including an increasing number of presentations for various target groups, panel debates, and media appearances.

We have continued our work to influence and shape the societal and media landscape connected to plastics with regular contributions to niche publications, and press releases aimed at highlighting our research to the plastics industry and members of the general public.

Some examples of our outreach work are STEPS participation in Almedalen in July, where STEPS PhD student Karl Holmberg participated in a panel debate organised by Mistra on the theme: Are less plastic types the solution?; and STEPS participation at Naturvårdsverkets conference for the plastics sector in September.

Our researchers' expertise continues to be seen as valuable to actors outside of academia, and in the policy realm: STEPS researcher Fredric Bauer contributed to the European Environment Agency expert workshop: Pathways toward circular plastic: Examples from countries and business, in October, whereas STEPS researcher Teis Hansen was appointed to the Danish Government's expert group on the role of research in the green transition, under the Ministry of Higher Education and Science. Teis Hansen was also appointed as a member of the Danish Football Association's Sustainability Committee, where plastics is a core sustainability topic.

Selected articles in the press and popular science journals

- Dagens nyheter, 21/2: Regeringens nya plan: Så ska Sverige minska plastsvinnet.
- Aftonbladet, 14/3: Rysk olja kan gömma sig i din hudkräm.
- Lunds universitets nyhetsbrev Apropå, 22/10: Fast i plast: koldioxidinlåsningar försvårar omställningen
- Nationell plastsamordning newsletter, 25/10: Fast i plast: koldioxidinlåsningar försvårar omställningen
- Dagens Industri, 26/10: Därför sitter plastbranschen fast I fossilberoendet.
- Aktuell Hållbarhet, 26/10: Forskare: Därför är plasten inlåst i fossilberoende.
- Polymervärlden, nr 7: Koldioxidinlåsningar försvårar omställningen
- Polymervärlden, nr 8: Så kan användningen av biobaserad plast i livsmedelsförpackningar öka.

Conferences

S Dash, A Nordin. Effects of print orientation on the design of additively manufactured bio-based flexible lattice structures, lecture at the *Proceedings of NordDesign 2022*, in Copenhagen, Denmark, 16–18 August 2022.

T Hansen. How Transformative are bioeconomy policies in the Nordic countries? Lecture as part of the *IFRO research seminar series*, 22 April 2022.

T Hansen. The (circular) bioeconomy transition. *A SINTEF Research seminar*, 3 March 2022

S Mankar. Vanillin-based spiroacetal monomer for improving chemical recyclability, thermal, mechanical, and barrier properties of polyesters. Poster presentation at the *Nordic Polymer Days*, Gothenburg, 1–3 June 2022.

T Nguyen. Homovanilic acid based sustainable polyesters. Poster presentation at the *Nordic Polymer Days*, Gothenburg, 1–3 June 2022

N Warlin. Synthesis of bio-based polyurethanes towards sustainable textiles. Talk at the *Nordic Polymer Days*, Gothenburg, 1–3 June 2022.

7) **N Valsange.** Synthesis, characterization and hydrolytic degradation of 2,5-furandicarboxylate copolyesters containing spiro cyclic ketal units. Talk at the *Nordic Polymer Days*, Gothenburg, 1–3 June 2022.

S Madsen. Axes of Contestation in the Waste Sector. Talk at the *6th Global Conference on Economic Geography*, Dublin, 10 June 2022.

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T Hansen. Next steps for transition policy research. Talk at the INTRANSIT & MIPO Workshop: *Mission-oriented and transformative innovation policy research: what are the next steps?*, Utrecht University, 6–7 October 2022.

R Hatti Kaul. Closing the loop: biocatalytic synthesis of polymer building blocks from renewable feedstock and recycled plastic, Invited talk at *Biocatalysis for the Biological Transformation of Polymer Science*, Köln, 27–29 June.

R Hatti Kaul, M Sayed, SJ Glaser, M Ismail, S-H Pyo. Biobased building blocks for recycled plastics via green chemistry and microbial transformations, Invited talk at the *International Forum on Industrial Bioprocesses*, Kaohsiung, Taiwan, 27–30 October 2022.

R Hatti Kaul. STEPS – Research program on transition pathways towards a sustainable plastic system. Guest Lecture held online for an EU project, Mix-Up, 4 November 2022

R Hatti Kaul. Sustainable Polymers and Transition Pathways. *Sustainability in Our Plastic World*, talk at the IDA, Copenhagen, 10 November 2022.

LJ Nilsson. IPCC och industrins omställning. Presentation for the Wallenberg foundation during a visit to Lund University, 14 March 2022.

LJ Nilsson. Hydrogen and the IPCC report, presentation for *the Oxford Institute for Energy Studies*, 22 June 2022.

LJ Nilsson. IPCC och industrins omställning, presentation för Sveriges ambassadör till Korea, 22 August 2022.

E Palm. Reaching net-zero in the chemical industry – a study of roadmaps. Talk at *Act Sustainable Research Conference*, Gothenburg University, 1 November 2022.

J Ahlqvist. STEPS – A research program seeking Sustainable Plastics and Transition Pathways, presentation at *Shaping The Future Of Packaging* arranged by Packbridge and Fempack, IKDC, Lund University, 9 November 2022.

OY Abdelaziz, ED Gomes, SV Mankar, CA Costa, B Zhang, AE Rodrigues, CP Hulteberg. Recovery of monoaromatic compounds from Kraft lignin toward the production of a potential green bisphenol A. Talk at *IUPAC International Conference on Green Chemistry* (9th ICGC), Zappeion Megaron, Athens, Greece, 5–9 September 2022.

Scientific publications

On the Oxidative Valorization of Lignin to High-Value Chemicals: A Critical Review of Opportunities and Challenges. *ChemSusChem*, 15(20), e202201232. Abdelaziz Omar Y, Ida Clemmensen, Sebastian Meier, Carina AE Costa, Alírio E Rodrigues, Christian P Hulteberg and Anders Riisager. 2022.

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STEPS board member
Rentus AB

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Programmes director at Mistra

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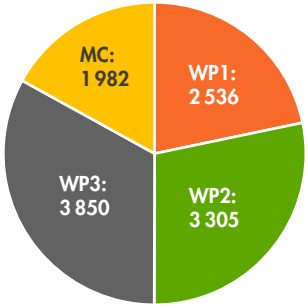
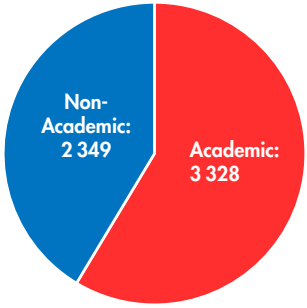
STEPS in Numbers

Total financial outcome 2022



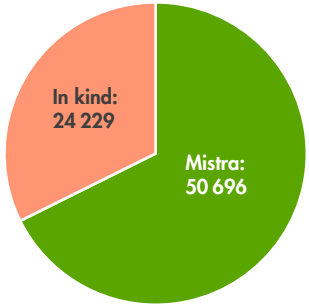
- WP1 – Renewable feedstock to polymer building blocks
- WP2 – Drop-in and new plastic formulation
- WP3 – Governance towards plastic transition
- MC – Board, management and communication

Total In kind contribution 2022



- Academic partners
- Non-academic partners

Total budget 2022



- MISTRA
- In kind

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