CATCHBIO

Ten years biomass catalysis

Highly selective and fast catalyst for biomass conversion

Young professionals about their destination

Turning lemons into whiskey and wood waste into nylon

Building a business on biomass

Responses from participants of the CatchBio final symposium in 2016 on the question:

What does 10 years of CatchBio mean to you?

A fantastic learning opportunity

An experience to build on further!

Ten years of accelerating the transition to a biobased society

The start of a new phase in my career

Deepening the connection between academic research and industrial applications to aid in the creation of a greener, cleaner world for future generations

Content

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CatchBio: Catalysis for Sustainable Chemicals from Biomass.

After ten years, the results of the CatchBio programme are impressive: almost 200 publications which have already been cited well over 4500 times, a strong network of academia and industry and some newly emerged players in catalysis of biomass... But when asked about which aspect of the programme's legacy he is most proud of, Scientific Director Bert Weckhuysen immediately replies: 'The people! CatchBio has been a success due to and because of the brilliant people involved.'

PROUD OF THE PEOPLE

How did CatchBio arise?

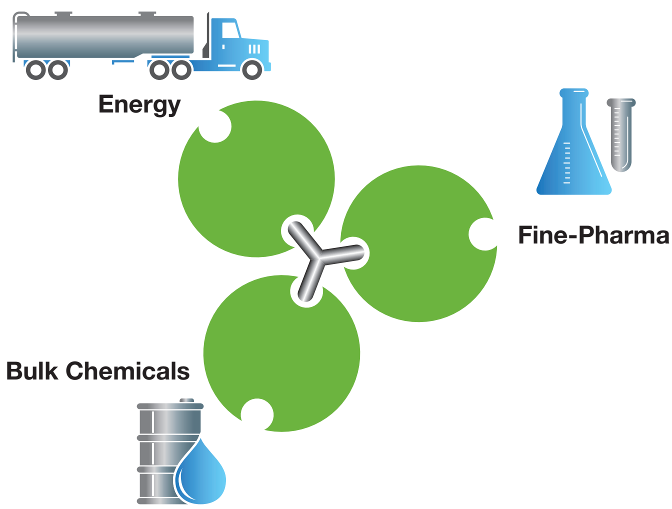
'Around 2005, the word on the street was that there was a large granting opportunity coming up for public-private partnership programmes. This later turned out to be the Smart-Mix programme, of which eventually only one round was organised. As a community of catalyst researchers, we immediately started to think about possible subjects for such a research programme. In chemistry, we have a long history of cooperation between industry and academia, and through the research school NIOK and the associated industrial partners, united in VIRAN, we already had an extensive network of people involved in heterogeneous and homogeneous catalysis. But for a large research programme to be granted, you always have to bring something new to the table. At that time some research groups in the Netherlands had been working on the catalytic conversion of biomass, but there was no cohesion in that field yet. At a series of brainstorm meetings we organised, we saw plenty of possibilities to significantly advance this field by a large scale, long-term research programme.'

This sounds like a pretty straightforward operation?

'It wasn't as easy as it sounds though. It took me as scientific director of NIOK a lot of time and personal visits to companies and research groups to form the definite consortium. People like Herman van Wechem, at that time president of VIRAN, also had to put in quite some effort to convince chemical companies to financially support this initiative. And the discussions about the consortium agreement, after being selected as one of the winners of the Smart-Mix competition, took up a lot of time and energy as well. The IP discussions, in particular, were very complex. I have to be very grateful to the continuous support from Utrecht University, especially former Dean of the Faculty of Sciences Professor Gerard van Koten and Yvonne van Rooy, former President of the Executive Board of Utrecht University. It is important to note that the CatchBio consortium is not a one-on-one copy of the NIOK-VIRAN combination. In this programme, we deliberately involved new partners, such as Avantium, ECN, Wageningen University and the Copernicus Institute for Sustainable Development. This had some nice side effects. Avantium, which was a small company at that time and not very well known at all, has grown to become a very important player in this field worldwide. And Wageningen University, which had plenty of experience in working with biomass but almost none in the heterogeneous catalysis field, has become a new member of the NIOK research school and has started its own catalysis group, led by CatchBio researcher Harry Bitter.'

What was the focus of the programme?
'In the first phase of the programme, we had defined three research clusters: energy, bulk chemicals, and fine chemicals & pharmaceutical intermediates. Later we have added a fourth cluster focussed on the socioeconomic aspects of catalytic biomass conversion. Back in 2006, we especially had high expectations for the fuels area. Biofuels, like bioethanol and biodiesel, were thought to have the future. When you look back now, that focus has shifted entirely during the ten years of the programme. The most promising application of biomass is now thought to be for the production of bulk and fine chemicals, as well as materials. Within the CatchBio programme we have demonstrated, for example, that levulinic acid can be transformed into chemical intermediates for bulk chemicals production. Eventually, we have had twice as many projects in bulk chemistry than in the other two clusters.'

CatchBio's research clusters



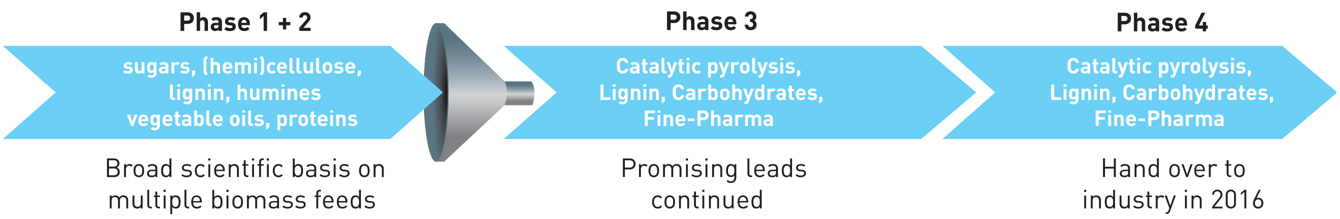
So not all research projects were defined right from the start?
'No, we used a Christmas tree-like structure for the programme. We started exploring a broad range of possible topics. Every principal investigator in the programme started with one PhD candidate. With every next phase in the programme, we selected the most promising routes to explore further. The other groups were asked to work together in larger research clusters to foster the best research directions. That was a unique approach for academic research back then: we were among the first to exploit a self-selecting mechanism.'

How has the research field changed during the past ten years?
'When we started, we were rather naive about the challenges biomass poses. The diversity in feedstock turned out to be tremendously bigger than in petrol-based resources. It matters, for example, what plant and what country the biomass originates from, how it has been processed, and how it has been cultivated. The composition of biomass is extremely complex and diverse, which makes it very hard to design processes and catalyst materials that will lead to reproducible and scalable results. Furthermore, society is not as enthusiastic about biomass now as it was when the programme started. Instead of focussing on using renewable resources (wind, solar, biomass or waste) the main focus has shifted towards the question: If you want to go from product A to product B, how can you do that in the most sustainable manner? That means using not only recyclable materials, but also taking into account product life cycles and lifetimes. If you use this chain approach then sometimes you even have to conclude that in some cases the petrol-based alternative can ultimately still be more sustainable than a process using biomass, for example.'

What is the relevance of CatchBio for these types of questions?
'Imagine that you indeed want produce something in a totally sustainable way. Now you can do that by choosing from different processes, such as biocatalysis, thermal conversions or homogeneous or heterogeneous catalysis. Within CatchBio we have created a library of technological possibilities to choose from with the catalysis option. Most probably, it will be the combination of these approaches, which will lead to the sustainable process of choice.'

CatchBio was a national programme. How does it compare to other research initiatives abroad?
'With this programme, the Netherlands was one of the forerunners in the field. It has acted as an inspiration for some comparable initiatives in the

CatchBio's innovation scheme



United States, such as PIRE and CBIRC, and for the UK-initiated SuBiCat consortium as well. On a more general note: The Netherlands has considerable experience in public-private partnerships, and we often act as an example for other countries.'

CatchBio has ended. What happens next?
'This programme as such has no formal successor. But of course there are many separate initiatives, which take individual results of the programme a step further. We have built a strong knowledge position in this research field, and now is the time to harvest. And I can't help but come back to the people who were involved in the programme. CatchBio has helped a new generation of excellent scientists and engineers to mature. And since the horizon of people is much longer than that of papers and patents, I have high hopes for the future of sustainable chemistry in our country.'

€29M
BUDGET

>30
PHD GRADUATIONS

>190
PUBLICATIONS IN PEER REVIEWED JOURNALS

>4.500
CITATIONS

Measured December 2016

STRONG BASIS

CatchBio originated partly from the existing organisations NIOK, the Netherlands Institute for Catalysis Research, and VIRAN, the Association of the Industrial Advisory Board of NIOK. Former president of VIRAN Herman van Wechem comments on the genesis of CatchBio.

Why did we need a programme on catalysis of biomass?
'At that time there was a strong emphasis on biotechnology for biomass conversion. The catalytic route, for which I had high expectations, had scarcely been explored. Using the very rich field of knowledge about catalysis from the oil and coal sector could be highly promising for biomass conversion.'

Were the industrial partners inclined to share the knowledge?
'Companies are eager to participate if you're going to build up new basic knowledge, which has high risk. This is knowledge that can easily be shared and that they can use later on for their own future business developments, so really pre-competitive research. An unavoidable aspect of the negotiations is the endless bickering about IP rights. This is and will always be a major stumbling block and one of the tricky things to solve.'

NIOK: Netherlands Institute for Catalysis Research
VIRAN: The Association of the Industrial Advisory Board of NIOK
PIRE: Partnerships for International Research and Education
CBIRC: Center for Biorenewable Chemicals
SuBiCat: Sustainable Biomass Catalysis

CatchBio in time

2006

The idea
setup a research consortium specialised in catalysis to explore opportunities in catalytic biomass conversion for the production of renewable energy, bulk- and fine chemicals.

Shaping the Smart-Mix proposal
During a meeting between NIOK (Netherlands Institute for Catalysis Research) and VIRAN (the industrial advisory board to NIOK), the future challenges and necessary research focus were discussed with prominent catalysis researchers in the Netherlands. This formed the basis for a research proposal in the Smart-Mix subsidy programme from the Ministry of Economic Affairs.

2007

CatchBio is officially announced
"Kansrijk Ceremony" – CatchBio is officially announced as one of the SmartMix programs. Scientific Director Bert Weckhuysen receives the Smart-Mix grant on behalf of the consortium alliance.

2008

1st Phase
The first selection of research projects is initiated within the research clusters Energy, Bulk Chemicals, and Fine/Pharma.

2009

Signing the consortium agreement
In 2009, all academic and private partners sign the consortium agreement, which enables the official start of Phase 1 research activities at the different participating institutes.

2nd Phase
The second selection of research projects is based on shared ideas on biomass catalysis between mutliple catalysis disciplines at different universities.

2013

ChemSusChem special issue: CatchBio
In September 2013, the renowned journal in Chemistry and Sustainablity, called *ChemSusChem*, dedicates a special issue to the research activities of the CatchBio consortium.

Initiation of the 3rd phase
2013 marks the start of the 3rd research phase in the consortium. Based on the results from the 1st and 2nd phase projects, the research clusters are redefined to focus on the following four topics: catalytic pyrolysis, lignin, carbohydrates, and fine/pharma.

2014

CatchBio video series
To reach out to the general public, a series of videos is produced in which CatchBio researchers explain the role of catalytic biomass conversion to achieve a biobased circular economy. The videos are shared on youtube and the CatchBio website.

Symposium: Uniting Renewable Catalysis Across Europe
Amsterdam – open symposium with TMFB Aachen and EaStCHEM (The Edinburgh and St. Andrews Research School of Chemistry)

2010

First progress meeting

Every year CatchBio organised a progress meeting to keep all consortium members informed on research developments.

Course Catalysis for Sustainability

Education of young researchers has always played an important role in the CatchBio consortium.

First user committee meeting

The user committee is organised twice a year, and allows PhD students and post-docs to present their results and interact directly with the industrial partners (the so called "users").

2011

Mid-term review

The Scientific Advisory Board is very positive about the consortium results. The output of this mid-term review was used to determine the focus of 3rd phase projects.

2012

Joint symposium TMFB & CatchBio

Research cluster TMFB (Cluster of Excellence Tailor Made Fuels from Biomass) based at RWTH Aachen University and CatchBio interact for the first time during a jointly organised symposium in Aachen, Germany.

2015

Symposium: New Concepts in Selective Biomass Conversion

Open symposium held in Aachen, jointly organized with TMFB and EaStCHEM.

Joint satellite symposium

Integration and synergy between biocatalysis and chemical catalysis for biorenewable conversions, joint satellite symposium CatchBio, with CBiRC (Center for Biorenewable Chemicals) and PIRE (Partnerships for International Research and Education) during the larger ISHHC conference on Homogeneous and Heterogeneous Catalysis in Utrecht.

4th phase

In 2015, the fourth phase of research activities was initiated, and promising leads from the 3rd phase were further investigated. The intitiation of the 4th phase demonstrated a continued interest from the private partners in the research activities of the consortium.

2016

Symposium: Tailored Catalysis for Sustainability

Open symposium held in Utrecht, jointly organised with TMFB and EaStCHEM.

CatchBio Celebrates!

Open symposium to mark 10 years of research on catalytic biomass conversion in the Netherlands, and celebrate with the community that made this possible.

Handover to Industry

The results from the research activities within the CatchBio consortium are shared publically in more than 200 peer-reviewed research papers. In addition, the research results from the academic partners are shared with the private partners in a dedicated handover-to-industry report.

1+1

Lignin is a difficult feedstock, because it consists of a network of tens of thousands of different molecules. Without cooperation research groups would only be able to focus on one or maybe two routes for breaking up lignin into valuable molecules. Erik Heeres and Emiel Hensen: 'By working together we could gain fundamental insight into more than twenty potential routes for lignin conversion.'

Emiel Hensen

Professor of Molecular Catalysis at the Eindhoven University of Technology

'Cooperating with other research groups with complementary knowledge and expertise for over ten years is very valuable, especially when it comes to lignin. Converting sugars mostly gives you two to three components. Breaking down lignin, however, is quite a different story. You easily get hundreds of products. For us it was difficult to hunt down all of the components by ourselves.

Access to the specialised 2D-GC analysis equipment of Erik Heeres helped us enormously. Analysing our soup in his lab using their expertise, resulted in information that we could use to track down the molecular mechanisms of the reactions that took place. We had a joint PhD student who was traveling frequently between Groningen and Eindhoven. Erik also taught us tricks about how to employ unusually high temperature and pressure to break down lignin.

Different routes

Besides working together with Erik's group, we cooperated with five other groups. This brought about an interesting approach. There are many routes for breaking up lignin, resulting in different end products. If everyone would stick to their own route, six groups could perhaps evaluate six routes. By cooperating we've gathered information about more than twenty routes. The participating companies really encouraged us to work this way, as they realised that it was too early to concentrate on a few routes. Nobody knows what a biorefinery will look like in five to ten years time or which products will become the most important ones.

Currently ten PhD students, about a third of my group, are working on biomass conversion, a theme that was new to us ten years ago. We were able to obtain funding from the European Union and Erik and I have new ideas for projects for which we hope to obtain funding. Even though oil and gas prices are low at the moment, I am convinced that in the coming decade biomass will become a viable resource for sustainable chemicals and results obtained within CatchBio will prove to be an excellent base for the development of sustainable processes by the European chemical industry.'

IS MORE THAN 2

Erik Heeres

Professor of Chemical Engineering at the University of Groningen

'Depolymerising lignin results in a complex soup. Together with the group of Emiel Hensen in Eindhoven we've analysed what kind of chemistry takes place when using novel homogeneous catalysts to depolymerise lignin. CatchBio brought our research groups together. Emiel and I had a joint PhD student in the second phase of CatchBio who mainly worked in Eindhoven and came to us in Groningen a few times for several weeks.

The soup we've made during phase 2 of CatchBio existed for more than 10 percent of interesting families of molecules, like alkylphenols and aromatics, which can be used as building blocks for resins and polymers. This encouraged us to go on. In phase 3 of the programme, we focussed our attention on heterogeneous catalysts, also commercially available ones, and on lignins with a lot of sulphur. Based on the results, both Emiel's group and ours made novel catalysts ourselves. We did experiments in which we changed the preparation of the catalysts and the process conditions, like pressure and temperature. The goal was to find the best combination of a catalyst with specific process conditions. A good activity and selectivity was needed, and especially over-hydrogenation to alkanes had to be avoided.

Get rid of the solvent

A breakthrough in our group was the idea to get rid of the solvent. We had previously used ethanol as a solvent. However, it turned out that lignin itself could function as a solvent too: It melts at temperatures below 200 degrees and as such the melted lignin acts as a solvent.

Eventually, we managed to increase the amount of interesting biobased building blocks to 30 percent based on lignin intake. In addition, we also scaled up the process and obtained litres of the upgraded lignin oils.

I really enjoy this kind of cooperation. I worked at Shell for over ten years. Joining forces in multidisciplinary teams happened all the time over there. When you cooperate with a complementary group, like we did with our Eindhoven colleagues, 1 + 1 is more than 2.'

Broadening network and expertise

Some of the partners that connected in the CatchBio programme had not worked together before. Due to its involvement in the programme, the contract research institute Wageningen Food & Biobased Research established a new network and a broader expertise, say Daan van Es and Jacco van Haveren.

'At the time CatchBio started, Wageningen University did not have its own catalysis group as it does now,' says Jacco van Haveren. 'At the FBR institute, we did have experience with catalytic conversion of biomass though. We did not work with model systems, but with the actual complex feedstocks.' 'At that time, most of the academic groups involved had ample knowledge about catalysis, but had not worked before with the complex mixtures raw biomass is composed of,' adds Daan van Es. 'That's where our expertise in separating and analysing the different components was very useful.'

Changing role

The role of the institute changed over time, both researchers explain. Van Haveren: 'In the first two rounds of the programme, we mainly concentrated on determining which conversion would be the most important to pursue, to enable the transformation of a given feedstock into useful resources for bulk chemistry. The academic groups in Utrecht and Amsterdam then searched for the optimal catalysts to achieve this.' Van Es: 'During the programme, our institute moved from perceiving catalysis as an enabling technology to actually developing and characterising new catalysts ourselves. At the same time, the academic groups gained more knowledge about biomass as a whole. Eventually, we were able to exchange samples, compare results, and use each other's specific analytical techniques to gain more understanding about different conversion processes.'

Being involved in CatchBio has had several lasting effects on the institute, says Van Es. 'Our contacts with Dutch catalysis groups have been boosted, resulting in our membership of the Dutch catalysis research school NIOK. We were able to expand our own expertise, and we invested in new infrastructure: for example, at the start of the programme we had one high-pressure reactor, now we have 30 of those in our labs. ' Van Haveren concludes: 'Due to the CatchBio programme, we have been able to meet our ambition of truly closing the chain all the way from raw biomass and refining this into fractions, to synthesizing useful building blocks for new materials.'

INCREASING THE CHANCES OF SUCCESSFUL IMPLEMENTATION

The Copernicus Institute of Sustainable Development of Utrecht University was involved in the CatchBio programme from the second phase onwards and conducted techno-economic and environmental assessments. 'To identify which new technologies have the most potential, you need to take into account far more than just the costs,' states Andrea Ramirez.

Andrea Ramirez Copernicus Institute of Sustainable Development, Utrecht University

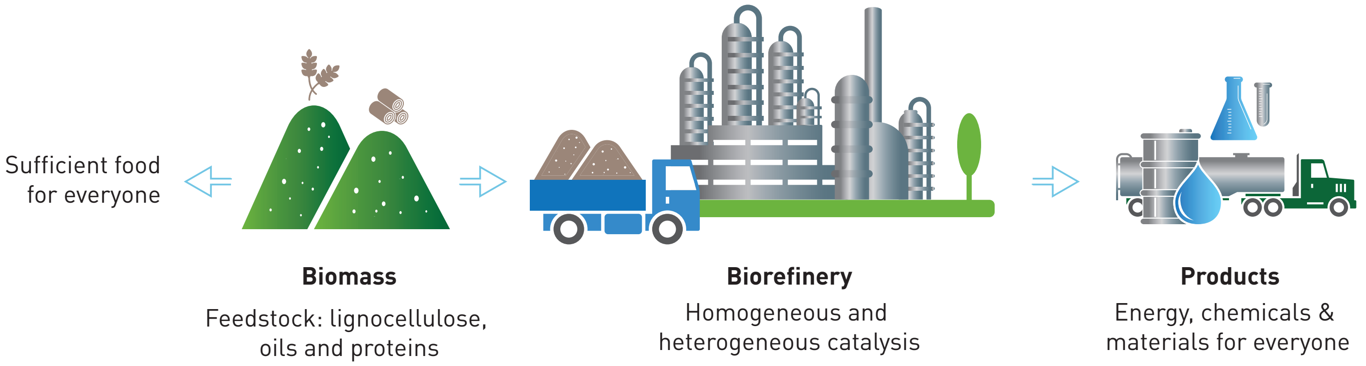
'At the Copernicus Institute, we already had considerable experience with investigating the possible impact of, and the uncertainties involved with, the development of biobased chemicals and materials. In the CatchBio programme, our role was to screen for the processes that could have the largest impact on industry and society, and to evaluate these extensively.'

The researchers delved into the most promising processes from the three different research themes to identify the possibilities, issues and bottlenecks of the new technologies. 'We literally started from the process design,' says Ramirez, illustrating the type of research she and her colleagues did. 'So we took the recipe the chemists had developed: "Take 10 grams of this, and mix it with 20 millilitres of that, for so many minutes at this heat and pressure." We scaled up the experimental data available to realise the production of 1 kilogram of a product, for example, and designed a process chain that would be able to process biomass at an industrial scale, of say 250,000 tonnes.'

'Then we calculated the energy and mass balances and compared those with current petrochemical based alternatives. We looked at things such as the amount of water consumed, the amount of heat needed or produced, the amount of CO_2 produced, reactor costs, and utilities costs. We took into account not only the process itself but the entire chain, starting with the harvest of biomass and ending with the product. This allowed us to gain an extensive, early stage evaluation of the feasibility and possible bottlenecks of implementing this process at an industrial scale.'

Sustainability beyond feedstock

When designing processes that involve renewable resources, it is important not just to calculate how much the final product would cost, emphasises Ramirez. 'Using biomass as feedstock, does not necessarily mean that your end product is more sustainable. For example, what if you need precious metals for your catalysts, or your process requires extensive heating, which is very energy consuming? Do you use toxic materials in your production process? And how safe will the process be for the workers involved? These are all issues that should be taken into account when developing new, more sustainable industrial processes that have a good chance of being implemented successfully.'



Industry taking part in a necessary transition

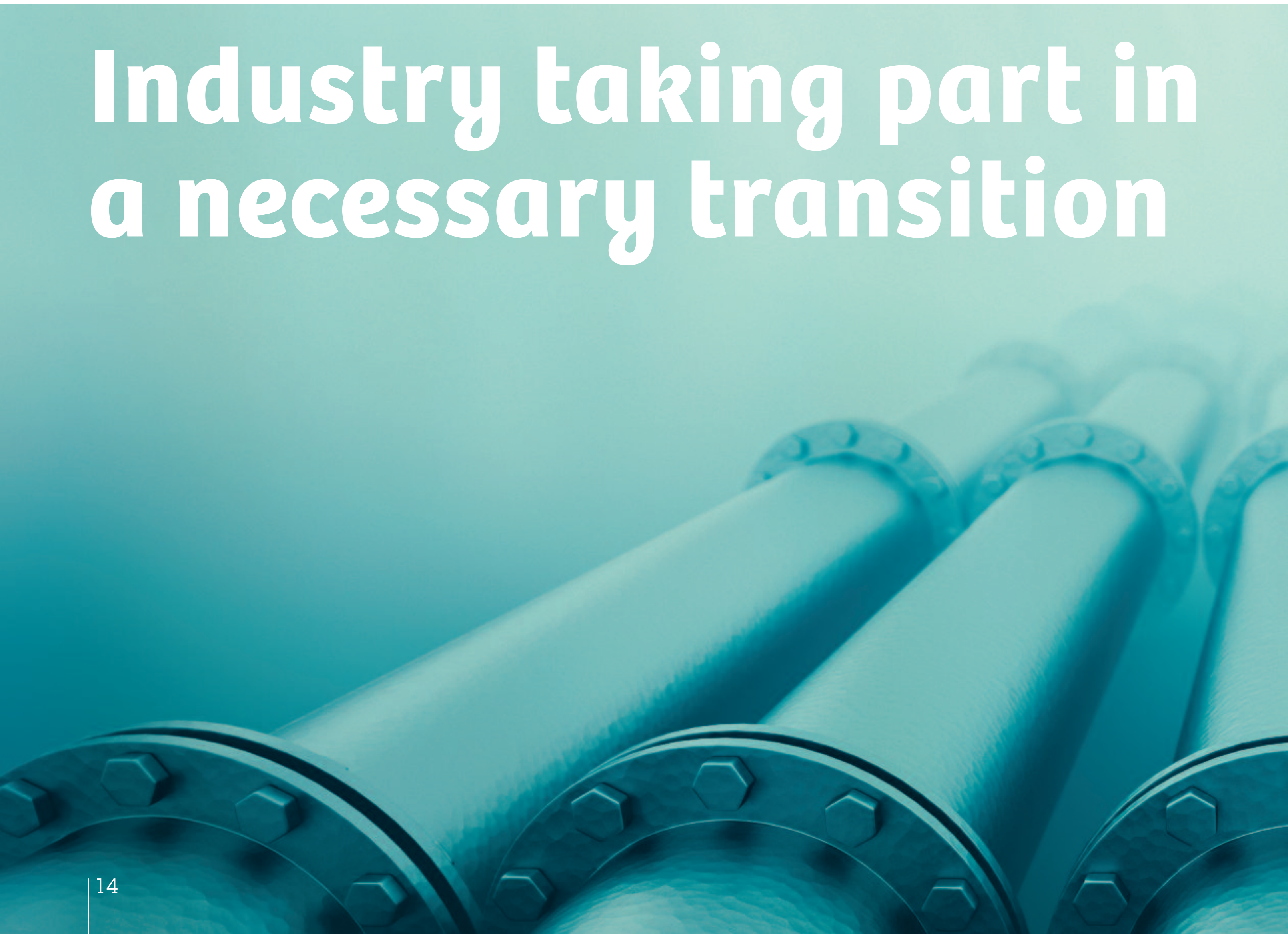
CatchBio is part of the investment programme Smart-Mix aimed at boosting innovation in the Netherlands. A substantial part of the programme's 29 million euros budget is financed by the 12 industrial partners involved. Five of the industrial partners in the CatchBio programme reflect on their involvement, the outcomes of the programme, and the challenges ahead.

'Most of our current chemicals originate in some way or the other from fossil resources. We now see a gradual shift towards more sustainable and alternative resources. This change to sustainable biomass is one of the existing trends, and as a leading company, we are actively engaged in these developments,' explains Peter Berben, Senior Research Manager at BASF. This is one of the reasons why his company got involved in CatchBio.

Complement industrial activities

For most of the industrial partners, the programme complemented their own activities in the field of renewable resources, as Hans Gosselink, Regional Manager Biodomain Shell Projects and Technology, illustrates: 'The Biodomain activities at Shell Technology Centre Amsterdam involve chemical, catalytic and thermal conversion of biomass to a next generation of biofuels and base chemicals. This is also one of the CatchBio objectives.' For DSM, the programme's activities in both the bulk and the fine chemicals clusters have been relevant for the company: 'The projects focused on sustainable chemistry and catalysis, and some of the ideas were picked up and further evaluated in our own labs,' says Michèle Janssen, Research Scientist at DSM Innovative Synthesis. 'By joining a consortium like CatchBio, you can share the costs for long-term future developments.' For the Shell spin-out Avantium, CatchBio also came along at exactly the right time, explains Vice-President Development Ed de Jong: 'We were at a point when we had to develop our own intellectual property, and we wanted to search for that in catalytic biomass conversion. That was a perfect match with the aims of the programme.'

Peter de Peinder, founder of VibSpec, took part in the consortium to gain access to new markets for his training, software and consultancy services in the field of



Vibrational Spectroscopy: 'I had a young company with ample contacts in the vibration field but virtually none in the catalysis field. This programme was my way of becoming acquainted with the people and the needs there.'

Educating the next generation

One of the outcomes of the programme highly valued by the industrial partners is the training of young people. Ed de Jong from Avantium: 'People who have been educated within CatchBio are very valuable for our company, since they have experience in the catalytic conversion of biomass field, as well as at least a basic idea of the constraints you need to take into account when you want to valorise research results.' This last topic is also highly valued by DSM, Michèle Janssen explains. 'For research to be able to be turned into actual industrial processes, it is important to train people from the start to have an open eye for the conditions needed. Often in a lab situation, researchers will use purified feed for their experiments to develop a new catalyst. But in real life, the impurities in renewables can shut down the entire catalyst.'

Besides this training aspect, the technological knowledge about the process of catalytic conversion of biomass is perhaps the most important result of the programme. 'The main outcome of the CatchBio consortium for Shell is knowledge on the fundamentals of catalytic conversion of biomass,' says Hans Gosselink. 'This knowledge from CatchBio is of interest for the future research within our own company.' 'BASF uses renewable raw materials for two reasons: On the one hand, we want to respond to the market pull resulting from consumer and retailer demand. On the other hand, renewable feedstocks make it possible to develop products with new functionalities and molecules that would otherwise not be accessible or less well accessible via fossil-based routes,' adds Peter Berben from BASF. 'Our active involvement in building up new innovative partnerships like ARC CBBC and strategic participations in new joint ventures like Succinity and Synvina is a clear case in point.'

Long-term commitment

Ed de Jong from Avantium underlines the time needed to achieve this development: 'A ten-year programme seems a long time, but even though we are a frontrunner in this field, it took us a decade to come to a joint venture towards commercialising our technology. You need to know the ins and outs of a new field before you can get the real creative ideas and start harvesting. That is the point we are at today.'

OPEN COLLABORATION WORLDWIDE

CatchBio is involved in SuBiCat, an international and EU-funded consortium that seeks to valorise lignin from biomass. This challenge can only be tackled by parties working together, says the consortium's founder Paul Kamer.

'The challenge of converting fossil feedstock into renewable resources is far too large for a single group or even a single country to solve alone,' says Paul Kamer, researcher at the University of St. Andrews, when he explains how SuBiCat took off. 'I know that Bert Weckhuysen feels the same about this and so I contacted him in 2012 to set up a consortium. Our expertise in homogeneous catalysis here at the universities of Edinburgh and St Andrews is complementary to that of the specialists on heterogeneous catalysis working within CatchBio.' The RWTH Aachen University cluster of excellence "Tailor-made fuels from biomass" (TMFB) was also involved due to their engineering knowledge. Other areas of expertise such as advanced spectroscopy and biocatalysis completed the EU-funded SuBiCat consortium.

The lignin case

SuBiCat aims to use lignin from biomass as a resource for chemicals. Lignin is a potentially valuable source of aromatic compounds for the fine chemicals used in the food and pharmaceutical industries, for pharmaceuticals such as the Parkinson medicine L-Dopa, or for bulk chemicals such as phenol. Lignin, however, is difficult to break down. SuBiCat has a holistic approach to this problem, says Kamer. 'We need methods to extract the small amount of very valuable chemicals from the lignin biomass. After this cherry picking, the leftovers can be sent to a biorefinery to make fuels, for example.'

Lignin valorisation is also a part of the CatchBio objective because it provides a mutual benefit in the exchange of researchers, knowledge and expertise. 'For example, we are trying to use oxidative approaches to break down lignin, but for me this is a new field. Bert Weckhuysen and Pieter Bruijnincx from Utrecht University have the knowledge and equipment needed for this research and our cooperation has resulted in a joint publication. Conversely, Nick Westwood from the University of St Andrews and Andy Smith from the University of Glasgow are our organic synthesis specialists, helping others within SuBiCat to prepare advanced lignin model systems and intermediates.'

TMFB focuses on the entire value chain from lignocellulose biomass to fuels. A key difference between TMFB and the other programs is its focus on fuels, explains Regina Palkovits, Professor of Heterogeneous Catalysis in Aachen. 'But the challenges that we are facing in breaking down lignocellulosic biomass are comparable. This shared interest is why our joint symposia are so fruitful.'

Interaction with industry

'The Netherlands is renowned and admired throughout the world for its knowledge of catalysis,' says Kamer. 'Researchers are astonished about how well this small country performs in an

FOR A CHALLENGE

intensive research field such as catalysis. The quintessence of the Dutch success is the interaction of academia with industry, for example part-time professorships of industrial researchers. The close collaboration between researchers from different institutes is also essential and this is aided by the short physical distances and the open-minded attitude in the Netherlands,' says Kamer. CatchBio has benefited from this open culture but has also shaped it by stimulating an open cooperation, he thinks.

'The unique, efficient and effective cooperation and transition to industry in the Netherlands are reflected in the CatchBio initiative'

REGINA PALKOVITS

As a former Utrecht University researcher, Palkovits agrees. 'The unique, efficient and effective cooperation and transition to industry in the Netherlands are reflected in the CatchBio initiative. The products and technologies are very application oriented and the cooperation with the industrial partners is strong.' In contrast, the German TMFB initiative receives funding explicitly meant for fundamental research. Both have their advantages, says Palkovits: 'The Dutch way leads to a very good early feedback on what the challenges and opportunities are for the market. The German system yields the opportunity for off-the-road research, but at a certain point competitiveness has to be proven.' SuBiCat will end in October 2017, but in view of the current Brexit developments, the future is fairly uncertain, says Kamer. 'We will be discussing a continuation, and I hope that we will be able to keep cooperating with the main European continent in the years to come.'

SuBiCat

Sustainable Biomass Catalysis

What?

An international collaboration between researchers from CatchBio, EaStCHEM (the joint chemistry research School of the Universities of Edinburgh and St Andrews) and the RWTH Aachen University cluster of excellence 'Tailor-made fuels from biomass' (TMFB).

Why?

To bring together all of the expertise needed to convert lignin from biomass into valuable chemical building blocks.

Who?

Six academic partners across the EU, one Dutch industrial partner and six associated partners from industry.

When?

2013 to 2017.

How?

With 4 million euros in funding from the EU, twelve PhD students and three postdoctoral researchers are funded, and an additional twelve principal investigators are involved.

DIVING INTO THE

> **One day pharmaceutical companies will probably need to use biomass based rather than oil-based molecules for their medicines. CatchBio brought together two research groups that were a good match for turning a chance finding in this field into a promising innovation. Hans de Vries and Joost Reek: 'We've both learned a lot from this cooperation.'**

Hans de Vries

part-time Professor of Homogeneous Catalysis for Fine Chemicals at the Stratingh Institute for Chemistry, University of Groningen and currently a professor at the Leibniz Institute for Catalysis in Germany

'Carbon-carbon bond forming reactions are very important when it comes to converting small sugar molecules from lignocellulose into more complex molecules that can be used by the pharmaceutical industry. Through a chance finding in an earlier project we discovered that in a reductive carbon-carbon bond forming reaction amines do a better job as a reducing agent then formic acid does. This increases the applicability of this type of reaction, which is good news for the environment, since the older methodology uses metal-based reagents that cause metal waste.

Finding the mechanism

We did not have a clear idea about the mechanism of this reductive step though: different theories could apply. However, if the reaction is to be improved to allow industrial application then the mechanism needs to be known. And this is where Joost Reek came into the picture. His group is specialised in unravelling reaction mechanisms by using elegant kinetic studies and labelling experiments.

For his group it was very important to develop a good protocol for the synthesis to make it as reproducible as possible. We talked a lot about how to do this. One of the things we changed was our solvent.

Eventually, based on our new knowledge about the mechanism, we were able to develop a process that uses 90 percent less catalyst. Furthermore, we discovered one catalyst that could make a single enantiomer (only one of a pair of mirror-image stereoisomers). For the pharmaceutical industry, catalysts that only produce one enantiomer are of great value, because otherwise they have to throw away half of the molecules produced.

I really enjoyed teaming up with a group specialised in mechanistic research. When we got a very critical review on an article we wrote, we worked in close cooperation to convince the reviewers that our proposed mechanism was correct. It was great to be able to use knowledge from two groups with different specialisations and to be able to convince the reviewers together.'

UNKNOWN **TOGETHER**

Joost Reek

Professor of Supramolecular Catalysis at the University of Amsterdam

'Answering someone else's research question was an interesting exercise. Usually we work on reactions and concepts that we have discovered ourselves, but it was inspiring to see how our expertise can be of use to rapidly unravel the mechanism of a reaction that's new to us. Questions from industry generally involve specific reactions and catalysts that we are familiar with, and in that respect the question from Hans de Vries and Adri Minnaard (both from Groninge University) was different. I've always liked programmes like CatchBio, because these large programmes enable you to work together with people in other chemistry fields on interesting topics.

In our project with Hans we focussed on a novel C-C bond forming reaction that at the same time leads to a chiral centre in the molecule. Our job was to unravel the details of the reaction mechanism. Detailed kinetics studies in combination with labelling studies and so called DFT calculation provided detailed insight in this reaction.

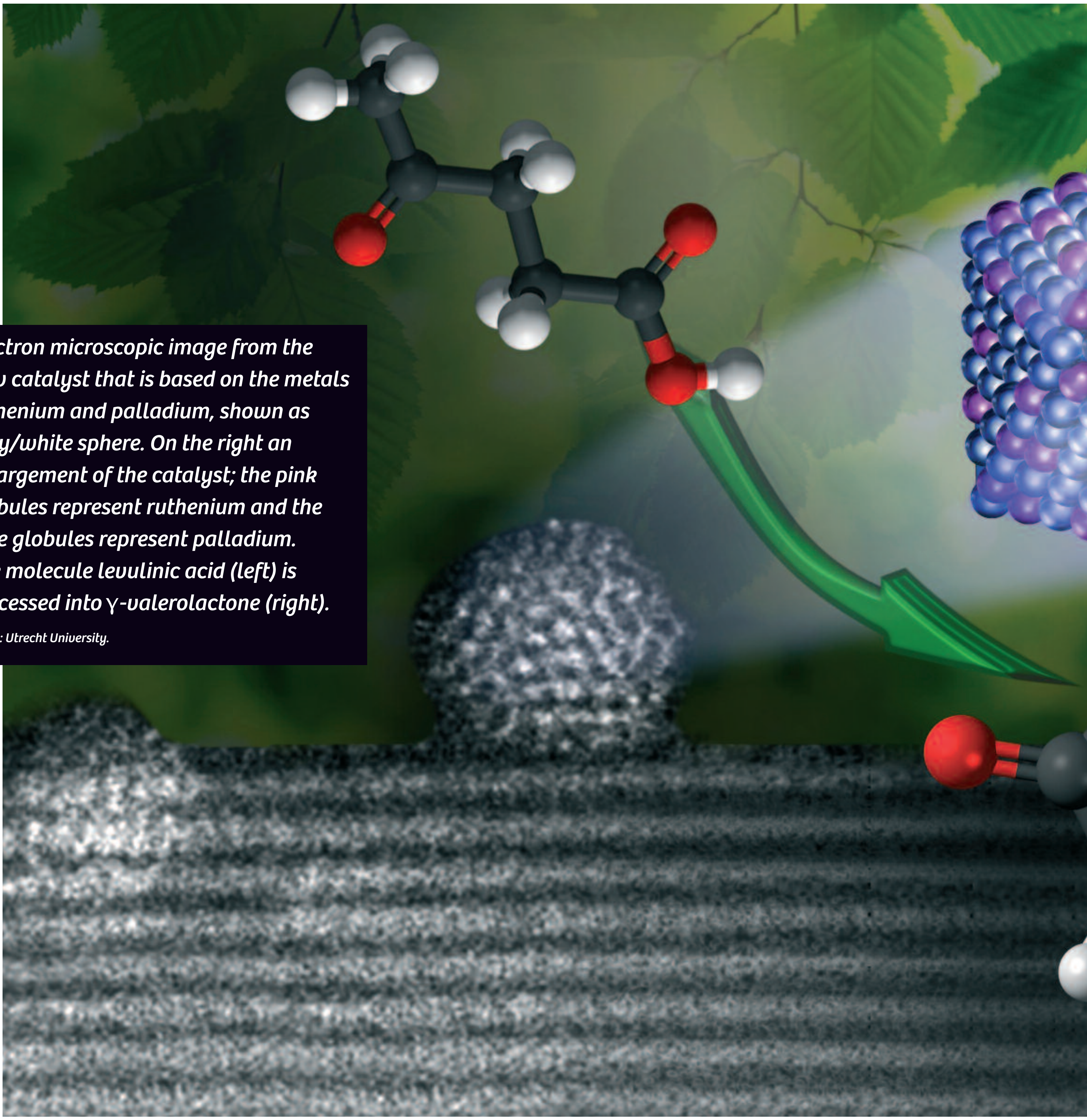
Industrially relevant

In this process, the postdocs from Amsterdam and Groningen shared their results quite often and in such a way that they both worked with the same optimised conditions. At the end of the day, we provided process conditions and selective catalysts that are industrially relevant.

Our groups were a very good match, as in Amsterdam we prefer to look into the details of a catalytic reaction, preferable with a limited number of substrates, whereas in Groningen they have a stronger focus on the application of a catalytic reaction. For a reaction to become generally applicable, a catalyst should work reliably on a myriad of different substrates.

CatchBio gave my research group the chance to use our experience for biomass research and to demonstrate that our new concepts in homogeneous catalysis are also applicable in this research area. It's a pity that the cooperation will stop when CatchBio is finished as we would like to continue it if the necessary funding were available.'

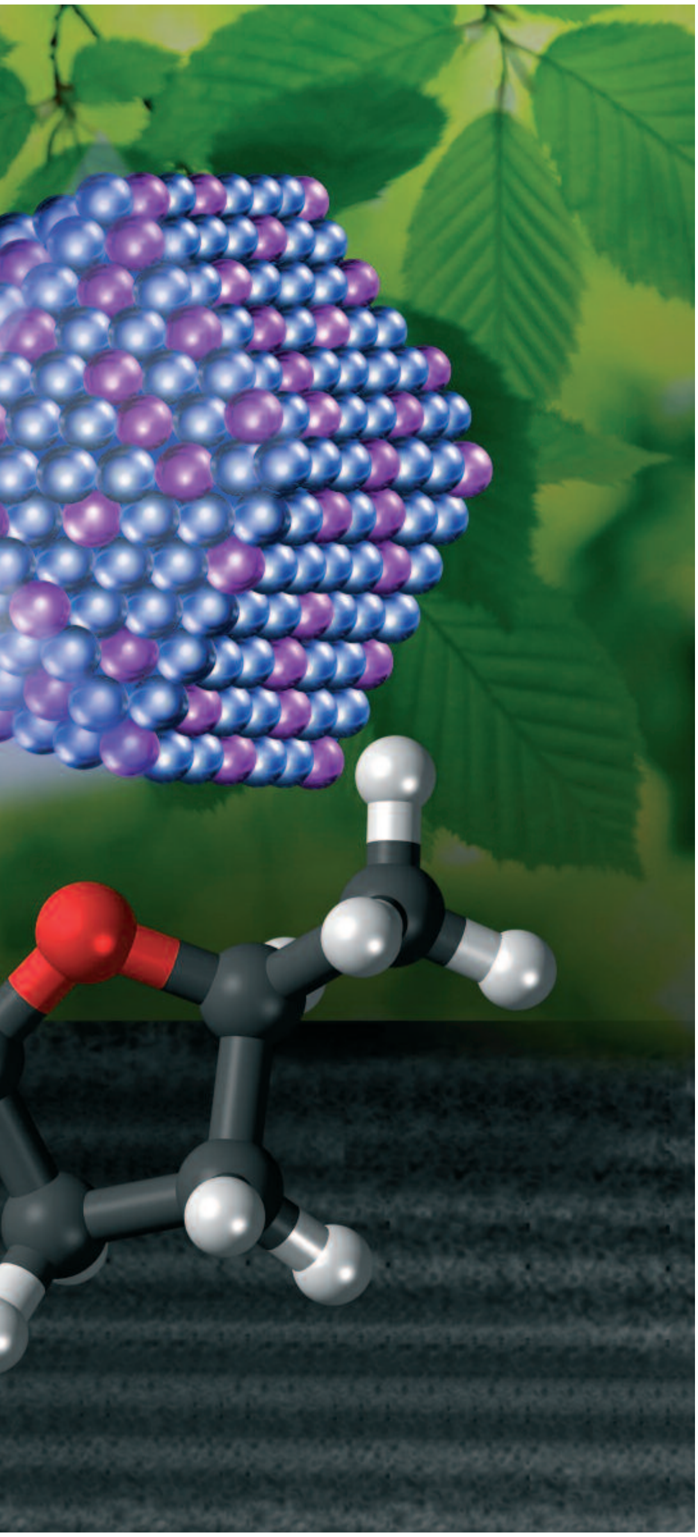
HIGHLY SELECTIVE



Electron microscopic image from the new catalyst that is based on the metals ruthenium and palladium, shown as gray/white sphere. On the right an enlargement of the catalyst; the pink globules represent ruthenium and the blue globules represent palladium. The molecule levulinic acid (left) is processed into γ-valerolactone (right).

Image: Utrecht University.

AND FAST CATALYST FOR **BIOMASS CONVERSION**



A stable, selective and fast catalyst for what is anticipated to become a key reaction within the biorefinery: that is what CatchBio researchers together with their colleagues from the UK and the US developed. They reported about their findings in *Nature Communications*.

Many routes have been proposed to convert non-edible, lignocellulose from wood or dry plant material into renewable chemical building blocks. One of the most promising involves a biorefinery scheme in which the conversion of levulinic acid into y-valerolactone is a key step. Researchers from the group of Bert Weckhuysen and Pieter Bruijnincx at Utrecht University succeeded in designing and synthesising a new catalyst, which promotes this reaction faster and more efficiently than before. Through careful catalyst synthesis, supported nanoparticles containing the metals ruthenium and palladium could be obtained in a highly controlled manner. This resulted in a highly active, selective and stable catalyst.

New method

One of the problems with making such nano-alloys of metals is that it is hard to control their composition and particle size. To produce the catalytic nanoparticles, the CatchBio researchers made use of a synthesis method previously developed by one of the post-docs involved to fabricate gold/palladium alloys. In this so-called modified impregnation methodology, an excess of chloride ions is used to obtain nanoparticles with a very narrow particle size distribution and a quite homogeneous, random alloy composition. The intimate mixing of the two metals proved beneficial and gave rise to a material with superior catalyst properties.

'Ruthenium in itself is a highly active catalyst. But it sinters rather quickly into larger particles, thereby reducing its surface area and consequently its catalytic efficiency. Furthermore, because of its high activity it degrades the end product, resulting in unwanted byproducts. By adding palladium to the ruthenium, we obtain a catalyst which is still very active, but far more stable and selective,' says Bruijnincx.

Long-term project

The article was published in 2015, but that certainly was not the end of the research. 'In the meantime we have studied this catalyst and related catalyst compositions further, with a particular focus on long-term stability and the influence of the inevitable impurities in real feedstocks. Promising results were obtained and two patent applications have been filed so far.'

Throughout the course of the programme, many CatchBio projects and researchers made the headlines. Bas de Bruin and Lies Bouwman highlight two publications that caught the attention of a wider public.

NYLON FROM WOOD WASTE

'We are inspired by biomolecules and asked ourselves: what can we do with these? For example, levulinic acid can be produced from cellulose originating from wood chips or corn waste.

This molecule is only a few atoms 'away' from caprolactam, the raw material used for the production of nylon. During the industrial production of a kilogram of caprolactam from fossil feedstock, a staggering four to five kilograms of ammonium sulphate are produced as waste. Therefore, we have developed a new process using biomass as renewable resource in which only water is formed as by-product. This four-year project was funded by CatchBio.

Two steps in a row

First, we developed several new, clean reaction steps to convert biomass into so-called pentenamides, which are precursor molecules of caprolactam. Then, we used a catalyst to convert the pentenamides into our product. A new rhodium catalyst is the key here. The catalyst performs two steps in a row: it adds a carbon atom to the precursor molecule and then closes the ring to form caprolactam. Rhodium is a very efficient catalyst for converting one isomer of the reaction mixture, 4-pentenamide. However, it does not efficiently convert its twin brother, 3 pentenamide. In the laboratory, we used pure 4-pentenamide to prove the concept, but this means the process is not applicable to real life biomass conversion yet. We are currently testing a new palladium catalyst that converts different pentenamides, which is also less expensive than rhodium.

We filed a patent to protect this new and unique chemical process. However, improving the process to be commercially attractive may take more than ten years. We need a catalyst that can perform the reaction at least 100,000 times, the so-called the turnover number. The rhodium catalyst currently has a turnover number of only 100. Therefore we need more research.

This research has been published in several trade journals and popular science magazines both online and in print. Additionally, I use this subject to explain the importance of chemistry to a general audience, such as first-year students and their parents, by showing them what we do in our research. When I explain that we are developing clean routes to convert wood waste into nylon, people can see the relevance of our work and they become enthusiastic about it.'

Lies Bouwman,
Professor of Inorganic Chemistry, Leiden University.
This research was published in *ChemSusChem* in 2014.

Turning lemons into whiskey

'Our main focus is developing clean conversion processes for a sustainable society. One such process is the conversion of acids and esters into alcohols, a widely used step, for example, in synthesising plastics from biomass. Imagine converting lemon juice into whiskey: we faced a comparable challenge in tackling this conversion.

In industry, this process uses hydrides such as borohydride. These have some safety issues and create a massive amount of waste. By using a catalyst, we can prevent most of that waste. However, until recently the only feasible catalysts for this job were ruthenium or iridium. These are rare and expensive metals. Instead we proposed a soluble, homogeneous catalyst based on the cheap, widely available and safe cobalt. Within this CatchBio project and in cooperation with DSM, researcher Ties Korstanje set out to achieve this goal.

Remarkable outcome

We started this project with the idea that we would first convert esters into alcohols. Esters are very similar to carboxylic acids, but they are more reactive and therefore an easier target. However contrary to our expectations, the catalyst appeared to be even better in converting acids than esters. This is one of the remarkable outcomes of our research. On top of that, the first choice of ligands, the protective coat around the cobalt atoms, proved to be exactly right. We used a triphosphine ligand that forms the most efficient catalyst with cobalt. We tried many other ligands, but these were all less active.

The process takes place at just 100°C and 80 bar of hydrogen pressure and in many cases shows yields of over 95 percent. After optimisation, I believe this process will be feasible for a wide range of conversions for industrial processes. However, the required pressure may still be slightly too high for use in industry. We have successfully converted several substrates that originate from biomass, such as levulinic acid obtained from cellulose or wood waste and biomass-derived succinic acid, into precursors for green bioplastics, solvents or fibres.'

Bas de Bruin,
Professor of Homogeneous Catalysis, University of Amsterdam. This research was published in *Science* in 2015.

'Far-fetched dream turned into realistic option'

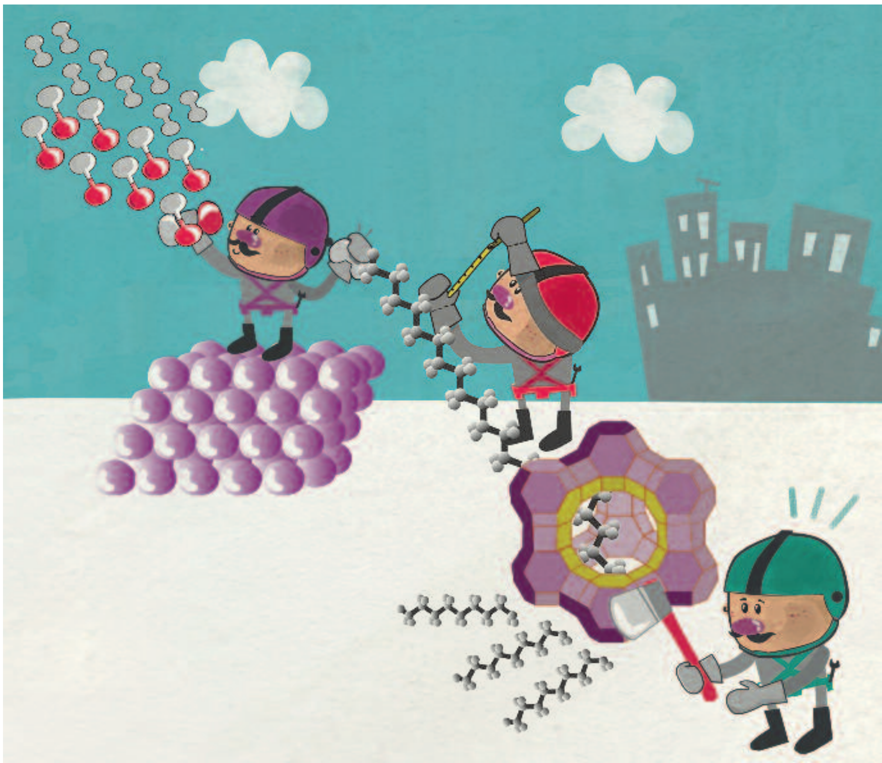
Colette Alma,
Director General VNCI

(Association of the Dutch Chemical Industry)

'When CatchBio started, the catalytic conversion of biomass was a dream. It was far-fetched. Due to the programme, the implementation of this idea on an industrial scale has become a realistic option. The programme's relevance is obvious: the chemical industry is facing a transition, in terms of energy and climate aspects. We need to consider the use of new types of resources for our chemical industry. Catalysis is a central discipline to achieve this transition to a more renewable way of producing materials.

It is hard to pinpoint which outcomes of CatchBio will eventually turn into commercial successes. But what we can see now, is that some of the partners involved are carefully stepping into biobased activities. There is a clear link between the achievements made in fundamental research during the last ten years, and the confidence with which companies are willing to take this idea to the next level.'

STICKY PORES FOR CONTAINER-SIZED PLANTS



The economic feasibility of small-scale liquid fuel production from biosyngas can be improved by combining two catalysts into one single catalyst particle, says Freek Kapteijn, Professor in Catalysis Engineering at Delft University of Technology. 'More and more people are taking up this idea.'

'The Fischer-Tropsch process, which converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons, is currently only used at very large scales by companies like Shell. However, if biomass is used instead of coal as a feedstock then a process that is economically feasible at a much smaller scale is needed. Otherwise large quantities of biomass need to be transported over long distances and that is simply too expensive.

We chose to combine two reactions using a single catalyst particle for both to make the reaction more efficient. The first step is the Fischer-Tropsch process that produces long molecules. In a second step these hydrocarbons need to be broken down into smaller molecules to make a liquid fuel.

Sticky substance

We put the cobalt needed for catalysing the Fischer-Tropsch process into a mesoporous zeolite made out of silicon oxide doped with some aluminium. This porous crystal uses it acid function to break up the long molecules. Sina Sartipi proved in his PhD thesis that longer molecules, in particular, prefer to stick in the pores. This is an interesting result because it is these longer molecules that need to be broken up.

We continued our research on Fischer-Tropsch process after the project financed by CatchBio was finished. This time we have used metal organic frameworks to convert syngas and our catalyst turned out to be ten times as active as the best one so far.

Our catalyst has attracted the interest of companies making container-sized, small operation units. These are not only interesting for biomass, but also when the available space is limited, like in the offshore industry. CatchBio made it easier for us to contact these small companies, because we had already met their people at CatchBio meetings and congresses. We have not developed any joint projects yet, but we hope this will happen in the near future.'

Cover: Catalysis Science & Technology
Credit: Jorge Gascon, TUDelft

Professional network for life

Annelie Jongerius, PhD
Junior Scientist Avantium in Amsterdam

Annelie Jongerius is just back from her two year postdoc in the department of Chemical Engineering at Stanford University funded by her NWO Rubicon grant. She worked on CO_2 hydrogenation and electrochemical CO_2 reduction for green fuels. 'I really wanted to go abroad, work in a foreign lab, learn new things. Although this research was still concerned with catalysis and renewable energy, the chemistry involved is entirely different from that in my CatchBio project.'

'During my Catchbio project on lignin at Utrecht University I had quite a lot of contact with the industrial partners who were enthusiastic about the work during the industrial committee meetings. Taking part in the annual progress meetings with other students and postdocs also helped me to learn more about the bigger picture in catalytic biomass conversion.'

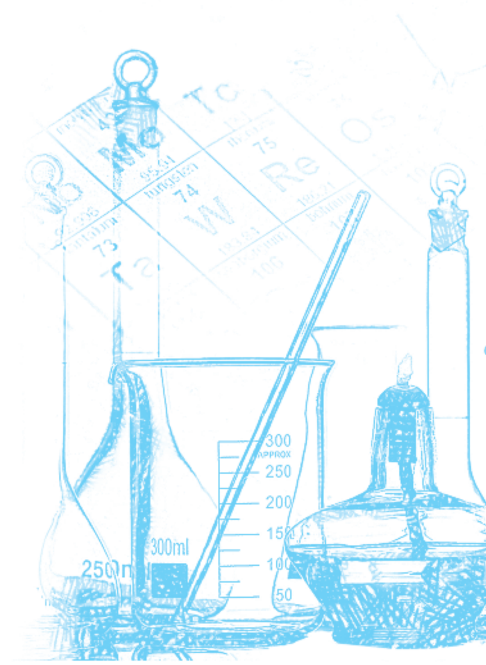
Now Annelie is working for Avantium as a junior scientist. 'Avantium is one of the companies with which I had a lot of contact with in CatchBio. The professional network I built during my CatchBio-time, in both the Dutch academic world and industry, has helped me in finding a job even three years after completing my PhD.'

Opening new horizons

Fernanda Neira d'Angelo, PhD
Assistant Professor Chemical Reactor Engineering at
Eindhoven University of Technology

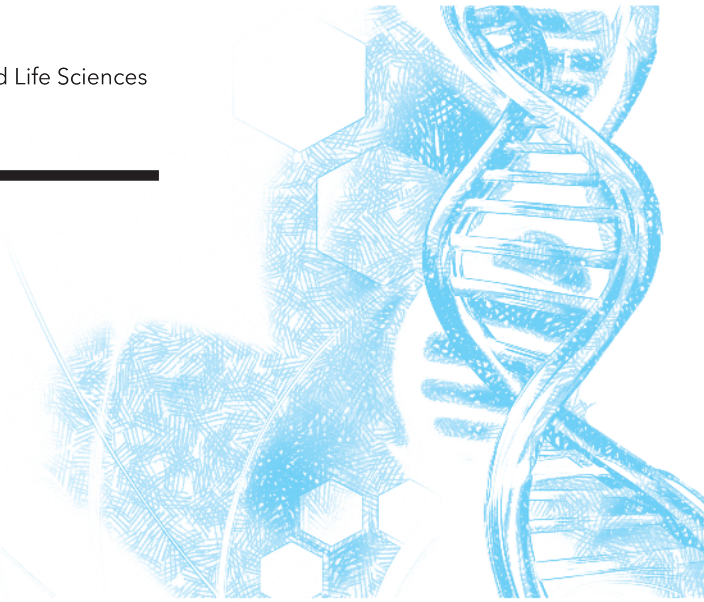
After completing her CatchBio PhD, Fernanda Neira d'Angelo started as a researcher at the small biobased startup company BiChem Technology. 'I wanted to gain experience in working in industry, to broaden my view while still doing innovative research. BiChem focuses on novel biobased technology and still does a lot of research. So it was perfect.'
'Catchbio offered a perfect surrounding to meet the right people. When BiChem was looking for a new employee, they contacted my supervisor, he recommend me, and I applied.'

A year later there was a vacancy in her former group for an assistant professorship. They were looking for someone with qualities fitting her profile, and contacted her. 'It was a difficult decision because I liked my job, but I realised it was now or never. I saw this as a unique opportunity that would broaden my horizons even more. So I applied.' Now she is happy to be back in the academic research world as a full time Assistant Professor at the Eindhoven University of Technology.



Into the world of patents and inventions

Henri van Kalkeren, PhD
Trainee Patent Attorney Chemistry and Life Sciences at V.O. Patents & Trademarks



It took Henri van Kalkeren a post-doc period at CPE Lyon to take the final decision and switch to a career as patent attorney in the field of chemistry and life sciences. The seed, however, was planted way earlier during his internship at DSM. 'For an invention we had made, a patent attorney came over to put it all in words. That was a very interesting and also creative process. But it was too soon for me to switch. Science was still too much fun, and I really thought I wanted to pursue a career in research.'

At the end of his CatchBio PhD project at Radboud University Nijmegen doubt settled in. Van Kalkeren did not perceive surfing from one post-doc to another, and entering in the game of acquiring research funding to be an attractive scenario for his future. He even considered a research career in industry for a while. 'Their goals are clear, and at the end there must be a product or process that is economically viable.'

But he hasn't left science completely. 'As a patent attorney you're always working with the latest research, and all the knowledge and experience I have gained during my study and PhD is essential.'

Best of both worlds

Rob Gosselink, PhD
Research Chemist at BASF the Meern

After his PhD project at Utrecht University Rob Gosselink started at BASF the Meern as a research chemist. He is involved in the development of catalysts, and as such still working in the same field of interest as CatchBio. 'I established my first contacts with BASF during my CatchBio PhD project as the company was represented in my Industrial Advisory Board. Their input was very valuable. As an academic you tend to lose yourself in the details occasionally.' So when he applied for a research job afterwards he rolled smoothly into the application process.

After four years basic research he longed for real processes and upscaling challenges. 'I always wanted to continue in research, especially the applied research. That's the beauty of my current job. My research group is within a production site including the factory. So what you develop in the lab, is being produced on the site. There is still a lot of contact with the academic world, so I don't lose sight. It is the best of both worlds.'

Making bio-oil suitable for refinery

Using a catalyst improves the quality of bio-oil made by pyrolysis (thermochemical decomposition at elevated temperatures in the absence of oxygen). The big question, however, is whether this improvement is large enough to compensate for the loss in quantity, says Sascha Kersten, Professor of Sustainable Process Technology at the University of Twente.

Sascha Kersten

Professor of Sustainable Process Technology
at the University of Twente.

'CatchBio gave me the fantastic opportunity as a process engineer to work with research groups specialised in the design of catalysts. It also gave me access to their advanced analytic instruments, like the 2D NMR apparatus in Groningen, which we could use for analysing the oil made in our reactors.

We already had a quite a bit of experience using pyrolysis without a catalyst, so-called thermal pyrolysis. CatchBio gave us the opportunity to enter the field of catalytic pyrolysis to make bio-oil.

Our aim is to improve the quality of the oil so that it can be used directly as a feed in a traditional refinery. That eliminates the need for the hydro-treatment step after thermal pyrolysis to remove oxygen from the oil and stabilise it. This represents a significant cost saving.

A too good catalyst

The catalyst we used at the start of this CatchBio project was too good. That may sound weird, but it speeded up the chemistry too much and as a result too much carbon and water were produced. The research group of Kulathuiyer Seshan developed less active catalysts. We tested them in our lab and in the labs of Erik Heeres (Groningen) and Paul de Wild (ECN). It really went back and forth; the research group of Seshan used our results to change the catalyst until we got a better one.

Oil made with the aid of this better catalyst, composed of sodium on alumina, is currently being tested in Delft, where they run a mini refinery, to check whether our oil can be mixed with synthetic oil. We hope the quality improved enough to compensate for the loss in yield.

Our process is not fussy when it comes to the kind of biomass. Wood, straw and hay can all be fed into the process. If industry is interested, they could start scaling up our process right away.'

The future of biomass conversion

What developments will the catalysis of biomass enable in the future? How will it change society? And which hurdles do we need to overcome before this vision can become reality? Six CatchBio researchers reflect on their hopes and dreams about the use of biomass for the future.

Chemistry paves the way

Evgeny Pidko, Assistant Professor of Molecular Catalysis at Eindhoven University of Technology

'I believe in the future of chemocatalysis instead of using enzymes to convert biomass into useful products. An enzyme needs energy and produces a lot of inorganic waste, often in equal amounts to the product it makes. The chemical catalytic route does not. Chemistry is often perceived as being not environmental friendly. But with chemistry we can achieve far better levels of efficiency than nature can.

I believe that eventually, we will move to a circular economy, regardless of the oil prices. Waste is a product. We have been working with biomass for only 15 years, and look at what we have achieved so far. The main problem we need to overcome is the current tendency to focus on the production of known chemicals. We should not mimic oil-based products, but instead come up with original ideas, unique concepts and novel chemistry to make new polymers with different properties. We should stop copying nature and be creative ourselves.'

Focus on energy

'On our way to a sustainable society, we should focus on alternatives for our fossils fuels based energy consumption. Energy consumption accounts for over ninety percent of all fossil resources use. If we find alternatives, whether that is in biomass, wind, or solar energy, we can keep using fossil resources as a basis for chemical products for hundreds of years to come.

As far as using biomass as a basis for chemical products is concerned, we need to keep this energy challenge in mind. We need energy efficient-processes. We should not invest a lot of energy in using biomass for the sake of using it. I strongly believe in the practical approach: choose what product to make out of the biomass waste based on the building blocks available in it. Take lignin for example. This can be converted into phenol, since they share elementary chemical building blocks. Or start using watery biomass to produce hydrogen using aqueous phase reforming, instead of wasting energy in removing water and oxygen to be able to turn the biomass it into valuable chemicals.

Xander Nijhuis, Chief Scientist at SABIC, Geleen

Solving petroleum problems by using waste

Katalin Barta, Assistant Professor of Synthetic Organic Chemistry at University of Groningen

'Lignin is the richest renewable source of aromatic compounds on the planet, so it is a very promising starting material for the future chemical industry.

There have been tremendous developments in the field over the past years. When we started, it was practically impossible to efficiently break down the robust structure of lignin. But now many new strategies have emerged. In my group we have also developed new strategies, and we are focusing on methods that are sustainable and energy efficient, based on cheap, abundantly available and non-toxic materials. If we can obtain aromatic products in high yields, we might be able to use them to partially replace the current petroleum-based chemistry.

I think it is great that ultimately we will be able to use a waste material for reducing our dependence on non-renewable petroleum.

Combination is key

'I don't believe in one winning approach towards a sustainable future. We need to work on different viewpoints and different products at the same time.

Harry Bitter, Professor of Biobased Chemistry and Technology at Wageningen University

Take the idea of using biomass as a feedstock for chemical products. There are two possible routes: either you use the biomass and convert it into a product that is already available and is currently produced from oil, coal, or gas. Or you stop focussing on what is already known, and develop entirely new products from the biomass, based on its specific properties.

Either way, for all new solutions we develop, we should take into account the entire production chain and its effects on the long term. Incorporating the circular idea, for example, also means that you base your solutions on green elements and materials, which are available in abundance. The key question is: How can we use available resources efficiently and repeatedly, whilst ensuring that we will be able to serve current and future needs with them.'

High-value applications

'Since the availability of biomass is not unlimited, I think we should see it as a resource rather than as waste and aim to use it for the highest value applications. With this in mind, we should make better use of the chemical complexity of the feeds that nature provides us with. Indeed, it is a bit of a waste to strip biomass of its precious functionalities to obtain the same petroleum-based building blocks we are currently using for polymer production. We should instead investigate how we can exploit the rich chemical structure of the biobased feedstocks to develop new products with improved properties. While such an approach will undoubtedly yield exciting science and novel ideas, it also comes with a significant hurdle: it is hard to implement new polymers, and prove their use and economic value.

Pieter Bruijnincx, Associate Professor of Catalysis for Renewables at Utrecht University

To further improve the viability of biomass valorisation strategies, we need to start looking at the entire production chain. Over the past few years, we have been working mostly on discipline-focused, isolated technological challenges, such as catalyst development for breaking down parts of the biomass to useful aromatic molecules. Now it is time to look beyond our own disciplines and to see how the different steps of biomass growth, collection, fractionation and further processing impact each other. We have been optimising the different steps. Now we should focus on optimising the sum of all of these technologies to actually turn biomass into a feasible alternative for petroleum.'

More holistic approach

'My PhD project concerned an analysis of the economic, sustainability and safety issues regarding new catalysts and chemical processes. My current company commercialises this knowledge by using data-driven analytics solutions. We assess and help find options for chemical products and processes that are the most sustainable, economically viable and safe in terms of environmental hazards and employee safety.

Akshay Patel, founder of Sustanalyze, Utrecht

If we want our world to become more sustainable then we must also consider the affordability of our solutions. And with that I mean not only for the rich western world, but also the poorer regions of our planet. Not everyone has access to sustainable energy or technology that increases life expectancy.
My dream is that we will be able to create a world in which we can produce energy, food, medicine and goods sustainably, safely and cheaply so that everybody's lifestyle can be improved in an affordable manner. We need to develop a more holistic view of sustainability and that is a transition which will be not so easy to make.'

‘Cooperation as a key competence’

Marjan Oudeman, President of the Executive Board of Utrecht University

‘As far as innovation is concerned, I strongly believe in the community idea: we have to create new things together. We are facing huge societal challenges: think of climate, energy, food. To cope with these, we need cooperation between universities, companies and societal organisations, and between different scientific disciplines.

In my view, scientific research should both focus on gaining new insights and on developing societal impact. To be able to achieve the latter, researchers must understand what is needed outside of the university walls. Therefore, we do not only want to teach our students to conduct research, but also train them in different competences such as thinking about the potential impact of your work on society and the how and why of cooperation. For our students, programmes such as CatchBio offer excellent opportunities to acquire those kinds of competences, which are crucial for their future careers, whether that is within or outside scientific research.’

Foto UU/Christiaan Krouwels

Building a business on biomass

A pilot plant in Geleen to demonstratie the newest technologies to converse biomass into useful chemical products on an industrial scale, and a joint venture with BASF to scale up production of biobased chemicals to 50,000 metric tons per year: over the past decade, CatchBio's industrial partner Avantium became a worldwide leader in renewable chemistry. CEO Tom van Aken looks back on the development of his company, and on what its involvement in CatchBio yielded.

Getting involved in the CatchBio programme was a good, but not an easy decision, remembers CEO Tom van Aken. 'Back in those days, we were one of the few industrial parties working on the catalytic conversion of biomass. So for us, the topic fitted exactly to the core of our business. But for a small company, we had to invest quite a lot of money into the programme, without any guarantees on its revenues.'

Looking back, Van Aken is pleased that he dared to step in. 'Through the CatchBio programme, we got a much better insight into the university groups active in this field. We are interacting a lot more with universities now than we did ten years ago. But perhaps the most important thing the programme brought us, is that we were able to hire a lot of good people, educated within the CatchBio-frame. We got the chance to follow them during their PhD research, and got to know their qualities well.'

Risky choice

In 2006, Van Akens company was one of the first to explore catalytic conversion of biomass. 'When I started at Avantium by the end of 2005, it was a services company offering R&D solutions for high throughput catalysis. The company needed to develop its own technologies and IP positions, and we choose to go into the direction of biomass conversion by the aid of catalysts.' That was a risky decision, since it was uncertain how long it would take before society and industry would actually make the transition to renewable resources. 'But I still strongly believe it is the inevitable way to go,' explains Van Aken the direction his company took.

The BASF chemical plant located in the harbour of Antwerp, Belgium.

So far, his decision has led Avantium into an adventurous and rather successful journey. In 2009, the company reported on developing a major breakthrough technology to convert plant-based sugars into chemical building blocks like furanics and levulinics. These are useful intermediates for the production of all kinds of plastics. 'At that same time, giant brands articulated their wish to go to 100 percent biobased plastics for their packaging,' Van Aken says about the way sometimes things get together. This led to a cooperation between Avantium and Alpla, The Coca-Cola Company and Danone for the development of 100 percent biobased so called PEF-bottles, based on the Avantium technology. PEF-bottles are not only more sustainable due to the biobased nature of the resources they are made of, and the fact that they can be recycled for 100 percent, but they also turn out to have other desirable advantages. For example, a PEF-bottle is less transparent for water, light and carbon, which elongates the lifetime of the product it contains.

Bright future in new materials

The latter illustrates nicely what Van Aken thinks the future of biomass should be: 'Biomass contains a lot of oxygen. Most people originally thought that we should remove the oxygen to be able to produce materials which resemble petroleum-based chemicals. But I think that is not a very smart approach: when you remove the oxygen, you are effectively throwing away more than half of the mass of the resource. Instead, we should develop a whole new class of materials based on the innate structure of the biomass, and then design new applications for these materials.'

The field is in a very exiting phase, the entrepreneur thinks. 'If I were to study chemistry now, I would immediately get involved in this field of research. Biomass is the future. Consumers are getting more and more reluctant to buy products which are oil- or gasbased. And biomass offers a lot of exciting new opportunities, we have only just started to explore. It is very nice that we have come to a point where one of our technologies is going to be scaled up together with BASF, but that is just the beginning. Now is the time for industry, academia and society to board this train and accelerate it.'

CatchBio Celebrates!

Final symposium 2016

APPENDIX

COMPOSITION OF GOVERNING BODIES

Management Team	
Prof. Bert Weckhuysen, chairman	Utrecht University
Dr. Hans Gosselink	Shell
Prof. Ben Feringa	University of Groningen
Dr. Jacco van Haveren	Wageningen Food and Biobased Research
Dr. Ed de Jong	Avantium
Prof. Lies Bouwman	Leiden University
Dr. Toon van Zijl	SABIC
Dr. Paul Alsters	DSM

Supervisory Board	
Prof. Gerrit van Meer, chairman	Utrecht University
Dr. Marcel Wubbolts	DSM, more recently at Corbion
Prof. David Reinhoudt	University of Twente
Prof. Alle Bruggink	Formerly at DSM and Radboud University
Dr. Herman van Wechem	Formerly at Shell

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Prof. Erik Heeres	Carbohydrates
Prof. Emiel Hensen	Lignin
Prof. Sascha Kersten	Catalytic Pyrolysis
Prof. Andrea Ramirez	Techno-Economic Evaluations
Dr. Laurent Lefort	Fine Chemicals/Pharmaceuticals

PROJECTS PHASE 1

ENERGY

Project	Title	Institutes	Project leaders	Researchers
053.70.001	Solid acid foams for a reactive extraction process for 5-hydroxymethyl furfural (HMF) production.	TU/e	Dr. Xander Nijhuis, Prof. Jaap Schouten	Shrikant Mohite, Vitaly Ordomskiy
053.70.002	Selectivity control in aqueous phase reforming	UT	Prof. Leon Lefferts, Prof. Kulathuiyer Seshan, Dr. Barbara Mojet	Kamila Koichumanova
053.70.003	Catalytic hydrolysis of cellulose: an alternative technology for the conversion of lignocellulosic biomass into sugars	ECN	Dr. Ruud Grisel	Jaap Willem van Hal, Arjan Smit
053.70.004	Aliphatic olefins from fatty acids (AlFA)	FBR, UU	Dr. Daan van Es, Prof. Harry Bitter, Dr. Jacco van Haveren, Prof. Krijn de Jong	Stefan Hollak, Frits van der Klis, Rob Gosselink
053.70.005	In situ valorisation of biomass: "From BioSynGas to liquid fuel"	TUD	Prof. Freek Kapteijn, Dr. Jorge Gascon	Sina Sartipi

BULK CHEMICALS

Project	Title	Institutes	Project leaders	Researchers
053.70.101	Decarboxylation of amino acids in the production of industrial chemicals	WUR, UT	Prof. Johan Sanders, Dr. Elinor Scott, Prof. Leon Lefferts	Gwen Dawes
053.70.103	Fundamental studies on the catalytic conversion of lignin and related model compounds in ionic liquids: Towards the development of a two-stage conversion route of lignin into aromatic compounds	UU	Prof. Bert Weckhuijsen, Dr. Pieter Bruijnincx	Annelie Jongerius
053.70.104	Catalytic partial dehydration of carbohydrates	UU	Prof. Bert Klein Gebbink	Ties Korstanje
053.70.105	Physical chemistry of catalytic sugar conversion	TU/e	Prof. Rutger van Santen, Prof. Emiel Hensen	Evgeny Pidko, Gang Yang
053.70.106	From lignocellulosic biomass to bulk chemicals. Development of efficient catalytic routes to 5-hydroxymethylfurfural (HMF) and derivatives	RUG	Prof. Erik Heeres, Dr. Ignacio Melián-Cabrera	Henk van de Bovenkamp
053.70.107	Development of (homogeneous) catalysts for the selective conversion of levulinic acid (LA) to caprolactam and for the conversion of furfural to tetrahydrofuran	UL	Prof. Lies Bouwman	Saeed Raoufmoghaddam
053.70.109	Catalytic staged degasification of biomass for the production of furfural and Levoglucosan	ECN	Dr. Paul De Wild	Ruud Wilberink, Jana Kalivodova, Ron van der Laan, Petra Bonouvrie, Gert Jan Herder, Claudia Daza

FINE CHEMICALS AND PHARMACEUTICALS

Project	Title	Institutes	Project leaders	Researchers
053.70.201	Selective catalytic substitution of hydroxyl groups by C- or N-nucleophiles	RU	Prof. Floris Rutjes, Dr. Floris van Delft	Henri van Kalkeren
053.70.202	Direct activation of allylic alcohols for alkylation and amination reactions	UvA	Prof. Joost Reek, Prof. Bas de Bruin	Yasemin Gümrükçü
053.70.203	Catalytic SN2-substitution of alcohols	TUD	Prof. Isabel Arends, Prof. Ulf Hanefeld, Dr. Kristina Djanashvili	Tobias Müller
053.70.204	Direct amination of alcohols via "hydrogen shuttling"	TU/e	Prof. Dieter Vogt	Dennis Pingen
053.70.205	Catalytic C-C bond formation	RUG	Prof. Ben Feringa, Prof. Hans de Vries	Celine Nicklaus
053.70.206	C-H Activation in asymmetric addition reactions	RUG	Prof. Adri Minnaard	Aditya Gottumukkala
053.70.207	Hydrogenolysis of Esters and Amides	UvA	Prof. Cees Elsevier	Eveline Jansen

PROJECTS PHASE 2

ENERGY

Project	Title	Institutes	Project leaders	Researchers
053.70.010	Development of catalysts for the conversion of bio-ethanol to higher value products such as 1-butanol and branched hydrocarbons as alternative fuels	UL	Prof. Lies Bouwman	Eric Gouré, Kapil Shyam Lokare, Yann Gloaguen
053.70.011	The development of a non-noble metal based catalyst system for the production of hydrogen from bio-feedstocks by aqueous phase reforming in a microreactor	TU/e, UU	Dr. Xander Nijhuis, Prof. Jaap Schouten, Prof. Harry Bitter, Prof. Krijn de Jong	Fernanda Neira d'Angelo, Tomas van Haasterecht
053.70.012	Depolymerization of lignin: towards gasoline fuel components	TU/e, RUG	Prof. Emiel Hensen, Prof. Erik Heeres	Burcu Güvenatam
053.70.013	Catalytic steps in the conversion of lignocellulosic biomass via pyrolysis to fuel precursors	UT, RUG	Prof. Kulathuiyer Seshan, Prof. Sascha Kersten, Prof. Leon Lefferts, Prof. Erik Heeres, Dr. Ignacio Melián-Cabrera Prof. M. Groeneveld	Masoud Zabeti, Nick Aldenkamp, Stijn Oudenhoven, Cassie Boyadjian, Teddy Buntara, Rajeesh Kumar Pazhavelikkakath Purushothaman
053.70.014	Solid acid catalysts for transesterifcation and esterification	UU, FBR	Prof. Harry Bitter, Prof. Krijn de Jong, Dr. Daan van Es,	Daniel Stellwagen, Frits van der Klis

BULK CHEMICALS

Project	Title	Institutes	Project leaders	Researchers
053.70.110	Biomass electrochemistry: from cellulose to sorbitol	UL	Prof. Marc Koper	Youngkook Kwon
053.70.111	Branched alcohols from (bio) alcohols via the gas phase Guerbet reaction	ECN, UU	Dr. Jaap Willem van Hal, Prof. Harry Bitter	Pirgon-Galin, Selvedin Telalovic, Ruud Grisel
053.70.112	Catalytic valorisation of lignin to key phenols and aromatics	UvA, FBR	Prof. Gadi Rothenberg, Dr. Daan van Es, Dr. Jacco van Haveren, Dr. Richard Gosselink	Frits van der Klis, Jacinta van der Putten, Rolf Blaauw, Stefania Grecea, Zea Strassberger
053.70.113	Catalytic routes for the valorisation of humin by-products formed during biomass processing	RUG, UT, UU	Prof. Erik Heeres, Prof. Kulathuiyer Seshan, Prof. Leon Lefferts, Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Yin Wang, Thi Minh Chau Hoang, Ilona van Zandvoort
053.70.114	Catalytic production of butadiene from bio-ethanol and non-fermentable sugars	UU, FBR	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx, Prof. Bert Klein Gebbink, Dr. Daan van Es, Dr. Jacco van Haveren	Carlo Angelici, Suresh Raju, Frits van der Klis, Linda Gootjes
053.70.115	Fundamental studies on the hydrogenation of bio-based oxygenates: Hydrogenation of levulinic acid to chemical intermediates for bulk chemicals production	RUG, UU	Prof. Erik Heeres, Dr. Ignacio Melián-Cabrera, Dr. Pieter Bruijnincx, Prof. Bert Weckhuysen	Anna Piskun, Wenhao Luo

FINE CHEMICALS AND PHARMACEUTICALS

Project	Title	Institutes	Project leaders	Researchers
053.70.210	Stereoselective iron-catalyzed CO- and CC-bond formation	RU	Prof. Floris Rutjes, Dr. Floris van Delft	Ferdie van der Pijl
053.70.211	Fine Chemicals from cashew nut shell oil. 3-Hydroxy-styrene and 3,5-dihydroxystyrene as building blocks	RUG	Prof. Hans de Vries, Prof. Erik Heeres	Sébastien Perdriau
053.70.212	Terpenes as starting material for nitrogen heterocycles using aza-Wacker, aza-Heck, and amino Heck reactions	RUG	Prof. Adri Minnaard, Prof. Hans de Vries	Manuel Jäger
053.70.213	Synthesis of (chiral) amines derived from biorenewable substrates	UvA	Dr. Jarl van der Vlugt	Michel Ferreira, Arnaud Perrier
053.70.214	Selective catalytic oxidation	RUG	Prof. Ben Feringa, Prof. Wesley Browne	Jiajia Dong
053.70.215	Renewable catalysts for renewable resources	RUG	Prof. Gerard Roelfes, Prof. Ben Feringa, Prof. Hans de Vries	Rik Megens, Almudena Garcia-Fernandez

SOCIO-ECONOMIC EVALUATION

Project	Title	Institutes	Project leaders	Researchers
053.70.301	Socio-economic assessment of fuels and bulk chemicals from biomass	FBR, ECN, UU	Dr. Martin Patel	Herman den Uil, René van Ree, Akshay Patel

PROJECTS PHASE 3

LIGNIN Coordinator: Prof. Emiel Hensen

Project	Title	Institutes	Project leaders	Researchers
053.70.331	Reductive lignin depolymerization by liquid phase reforming	UU	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Bo Feng
053.70.331	Two-step lignin valorization by sequential lignin depolymerization and lignin-oil HDO	UU	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Pengfei Yang
053.70.331	Multitechnique characterization of lignin and lignin-derived products	UU	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Sandra Constant
053.70.332	Catalytic hydrotreatment of Kraft lignin	RUG	Prof. Erik Heeres	Ramesh Kumar Chowdari, Yin Wang
053.70.332	Catalytic hydrotreatment of (depolymerized) lignins	RUG	Prof. Erik Heeres	Arjan Kloekhorst
053.70.333	Depolymerization of Kraft lignin under supercritical Methanol	RUG	Dr. Katalin Barta	Anand Narani
053.70.334	Catalytic valorisation of lignin to key phenols and aromatics	UvA	Prof. Gadi Rothenberg	Pepijn Prinsen
053.70.334	Catalytic reductive depolymerization of Kraft lignin using Ni3N/C catalyst under sub and supercritical	UvA	Prof. Gadi Rothenberg	Anand Narani
053.70.335	Towards an integrated catalytic processing concept for valorization of lignin	FBR	Dr. Jacco van Haveren, Dr. Daan van Es, Prof. Harry Bitter	David Franciolus, Arie van der Bent , Remco Simonsz, Rajeesh Pazhavelikkakath Purushothaman, Jacinta van der Putten, Richard Gosselink
053.70.336	Towards an integrated catalytic processing concept for valorization of lignin	ECN	Dr. Wouter Huijgen	
053.70.337	Lignin depolymerisation using hydrogen donors and Hydrotreating catalyst development for lignin depolymerization	TU/e	Prof. Emiel Hensen	Tamas Koranyi, Long Chen
053.70.337	Towards an integrated catalytic processing concept for valorization of lignin	TU/e	Prof. Emiel Hensen	Daniil Ovoshchnikov

CARBOHYDRATES Coordinator: Prof. Erik Heeres

Project	Title	Institutes	Project leaders	Researchers
053.70.351	Catalytic production of butadiene from bio-ethanol and non-fermentable sugars	TUD	Prof. dr. Freek Kapteijn, Dr. Jorge Gascon, Prof. Michiel Makkee	Filipe Vidal da Silva Lopes, Constantino Maldonado
053.70.352	Development of stable and selective heterogeneous catalysts for the hydrogenation of levulinic acid and its esters to g-valerolactone	UU	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Jamal Ftouni, Homer Genuino
053.70.352	Structural characterization of humins	UU	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Sandra Constant
053.70.352	Catalyst development for ethanol-to-butadiene	UU	Prof. Bert Weckhuysen, Dr. Pieter Bruijnincx	Sang-Ho Chung
053.70.353	Development of (homogeneous) catalysts for the selective conversion of levulinic acid (LA) to caprolactam	UL	Prof. Lies Bouwman	Yann Gloaguen, Bart Limburg
053.70.354	Catalytic gasification of humins to hydrogen	UT	Prof. Kulathuiyer Seshan, Prof. Leon Lefferts	Thi Minh Chau Hoang
053.70.355	Humines: Structural studies	TU/e	Prof. Emiel Hensen, Dr. Evgeny Pidko	Christiaan Tempelman, Juan Garcia Sanchez
053.70.355	Development of an integrated process concept for HMF synthesis	TU/e	Prof. Emiel Hensen, Dr. Evgeny Pidko	William van der Graaff, Christiaan Tempelman
053.70.356	Biobased bulk chemicals from carbohydrates; an integrated approach	FBR	Dr. Jacco van Haveren, Dr. Daan van Es	Willem Vogelzang, Linda Gootjes, Rajeesh Pazhavelikkakath Purushothaman, Arie van der Bent
053.70.357	Biobased bulk chemicals from carbohydrates; an integrated approach	ECN	Dr. Ruud Grisel, Dr. Paul de Wild	Claudia Daza, Raghavendra Sumbharaju

053.70.358	Catalytic depolymerization of humins and subsequent catalytic conversions to bulk chemicals	RUG	Prof. Erik Heeres	Shilpa Agarwal
053.70.358	Levulinic acid hydrogenation	RUG	Prof. Erik Heeres	Henk van de Bovenkamp
053.70.358	Development of an integrated process concept for HMF synthesis	RUG	Prof. Erik Heeres	Zheng Zhang, Peter Deuss
053.70.359	C6 sugars conversion into bulk chemicals	UR	Prof. Harry Bitter	Neus Blanch Raga, Tomas van Haasterecht

FINE CHEMICALS AND PHARMACEUTICALS Coordinator: Dr. Laurent Lefort

Project	Title	Institutes	Project leaders	Researchers
053.70.371	Tailoring metal-support cooperation for the selective hydrogenation of esters under mild conditions	TU/e	Dr. Evgeny Pidko, Prof. Emiel Hensen	James Pritchard
053.70.372	A scalable palladium-catalyzed reductive arylation	RUG	Prof. Adri Minnaard, Prof. Hans de Vries	Subramaniyan Mannathan
053.70.373	A scalable palladium-catalyzed reductive arylation	UvA	Prof. Joost Reek	Saeed Raoufmoghaddam
053.70.374	Selective catatytic oxidations	RUG	Prof. Wesley Browne, Prof. Ben Feringa	Emma Harvey, Apparao Draksharapu
053.70.375	Ester hydrogenation using cheap base metal catalysts	UvA	Prof. Cees Elsevier, Prof. Bas de Bruin, Dr. Jarl van der Vlugt	Ties Korstanje
053.70.376	Boosting organometallic-catalyzed C-H oxidation reactions in continuous-flow microreactors	TU/e	Dr. Timothy Noël, Prof. Volker Hessel	Nico Erdmann, Yuanhai Su

CATALYTIC PYROLYSIS Coordinator: Prof. Sascha Kersten

Project	Title	Institutes	Project leaders	Researchers
053.70.391	Catalytic pyrolysis	UT	Prof. Sascha Kersten	Danielle Castello, Annemarije Kooijman, Stijn Oudenhoven
053.70.392	Catalytic pyrolysis	UT	Prof. Kulathuiyer Seshan, Prof. Leon Lefferts	Songbo He, Christina Franch Marti
053.70.393	Catalytic pyrolysis	RUG	Prof. Erik Heeres	Louis Daniel
053.70.394	Catalytic pyrolysis	ECN	Dr. Paul de Wild	Raghavendra Sumbharaju, Raimo van der Linden, Ron van der Laan, Peter Heere, Paul Verbraeken, Herman Bodenstaff, Edwin Brouwer, Christiaan van der Meijden
053.70.395	Co-processing of catalytic pyrolysis oil in the microriser FCC unit	TUD	Prof. Michiel Makkee	Vijay Shinde

SOCIO ECONOMIC EVALUATION Coordinator: Prof. Andrea Ramirez

Project	Title	Institutes	Project leaders	Researchers
053.70.381	Socio-Economic assessment	UU	Prof. Andrea Ramirez	John Posada, Iris Vural Gürsel, Jonathan Moncada

Industrial partners

Academic partners

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Responses from participants of the CatchBio final symposium in 2016 on the question:

What does 10 years of CatchBio mean to you?

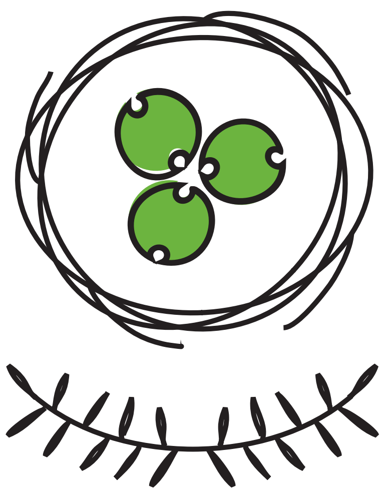
A promising bio-based journey has started with CatchBio and now it is the time to look beyond

10 years of top-class research and collaboration

Amazing platform in the field of biomass conversion and catalysis

Great scientific exploration in achieving sustainable chemistry

An excellent example of academic/industrial partnership to realise sustainable solutions for current and future societal needs



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