
INAUGURAL ADDRESS
Prof HG Brink
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- Good evening, colleagues, friends, and family.
- It's both a privilege and a pleasure to deliver this inaugural lecture, and to share with you the research journey that brought me to this point.
- Consider the title of this talk, *'Closing the Loop: Waste Valorisation as the Pattern for Sustainable Innovation'.* It reflects both a personal and professional narrative – one that has been shaped by curiosity, collaboration, and a deep commitment to sustainable development.
- Throughout this presentation, you'll notice a recurring theme – a woven pattern, symbolising how different research threads come together to form a cohesive fabric. Much like the image on this slide, these threads interlace biology, chemistry, engineering, and innovation in pursuit of a more circular, resilient, and responsible future.
- Let's begin at the start of the thread: how purpose, people, and problem-solving came to define my research trajectory.

1. Introduction: A Golden Thread

Weaving Purpose into Research

Why am I personally doing this research?

“Be part of the solution and not part of the problem”

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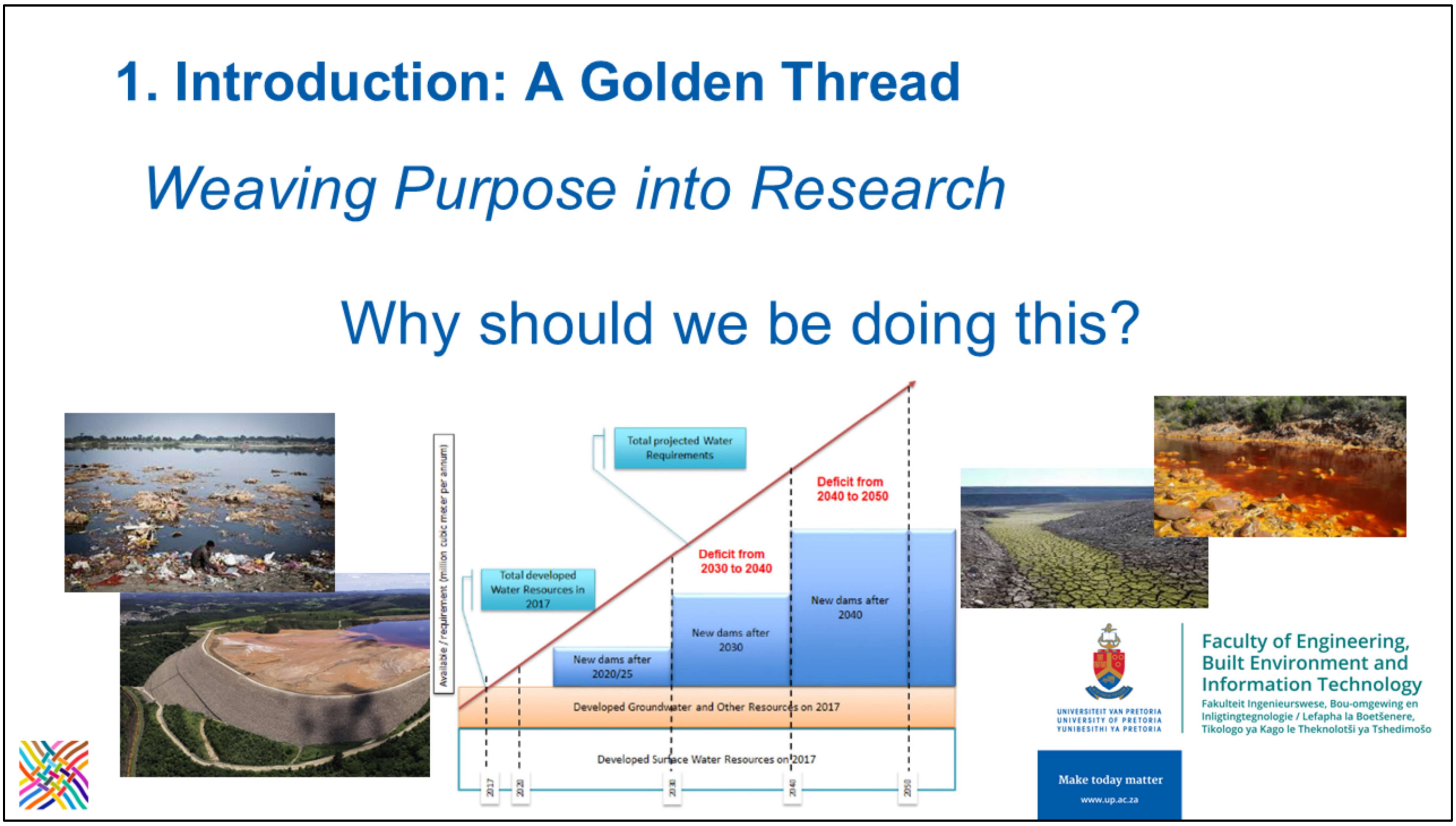
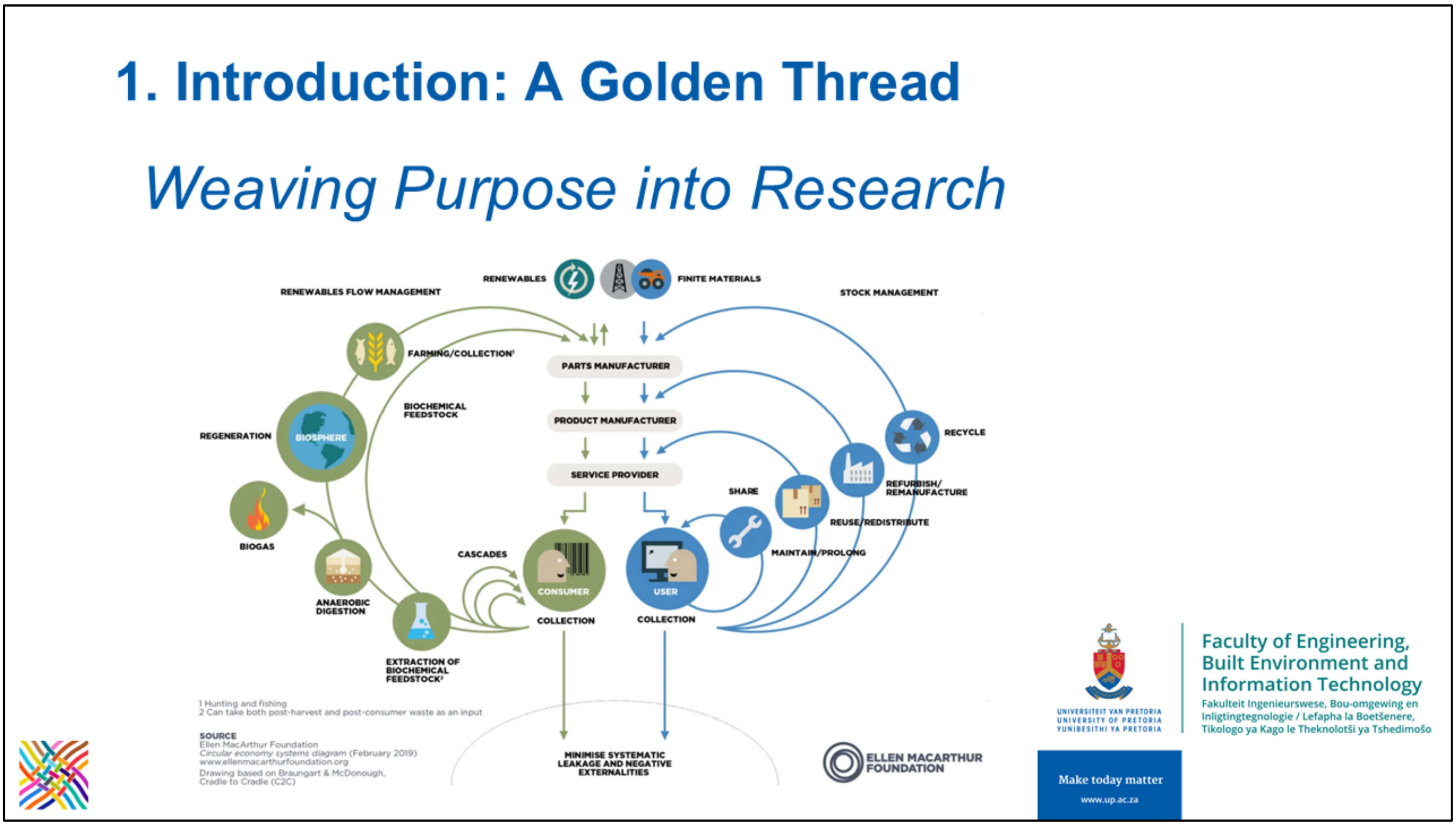
- “Let me start with something deeply personal. This journey—this research—isn't just a job or an academic pursuit for me. It's something woven into who I am.
- I often refer to myself as a bit of a *‘hippy engineer’*. I care deeply about the planet, about people, and about doing things differently—sustainably. And that's not just philosophy. It's what drives every decision I make in research and in life.
- I’ve always believed that our work should have meaning beyond publications and metrics. That’s why the idea of *weaving purpose into research* became my golden thread. It’s about being conscious, intentional, and connected to the bigger picture.
- The question that guides me is: *Why am I doing this?*
- And the answer is simple:
  Be part of the solution, not part of the problem.
- That quote captures the spirit of this work—and perhaps also the spirit of the guy in the image here. Colourful, unconventional, but determined to make a difference. And a little like me, I guess.
- In this lecture, you’ll see how that idea—waste as a problem, but also as a solution—became the pattern that links all of my work.”



- Let's take a step back and ask the foundational question:
  "Why should we be doing this?"
- We are living in a time where the environmental stakes have never been higher. We're seeing the consequences of **pollution, climate change, water stress, and resource depletion** unfold in real time – in our rivers, our groundwater, and the very air we breathe.
- 🔹 *On this slide, you'll see images that should make us all uncomfortable.*
  They reflect the **symptoms of linear systems** – where waste is generated faster than we know how to deal with it, and natural systems are pushed to breaking point.
- The **graph in the centre** shows projected water resource deficits. South Africa is forecasted to experience increasing water scarcity from as early as 2030 — a crisis compounded by mismanaged waste, pollution, and extractive industry legacies like acid mine drainage.
- So, **why do this research?**
  Because the current trajectory is unsustainable.
  Because engineering must move from being part of the problem to being part of the solution.
- And honestly, as I said earlier — and I say this partly tongue-in-cheek — I see myself as something of a **"hippy" engineer**.
  Someone who believes that **science and soul can work together**, that **technical solutions must have heart**, and that **purpose should weave through our research like a golden thread.**
- This is the motivation behind everything I'll be sharing with you tonight.

- "As we continue this golden thread of purpose in research, we must ask not just *why*, but *how*. How can we contribute meaningfully in the face of increasing environmental degradation and growing resource pressures?
- The answer, I believe, lies in reimagining waste – not as a burden – but as a valuable resource. This question, *'How can waste be reimagined as a resource?'* has guided much of my research over the past decade.
- And at the heart of this lies the concept of the **circular economy**. We need to shift from linear models of consumption and disposal, to circular approaches where materials are continuously cycled back into the system. Not only does this reduce environmental impacts, but it creates new value streams, economic opportunities, and social innovation.
- My goal is to embed this mindset deeply into the research we do – to engineer systems where waste becomes the feedstock, and scarcity becomes abundance through clever design."



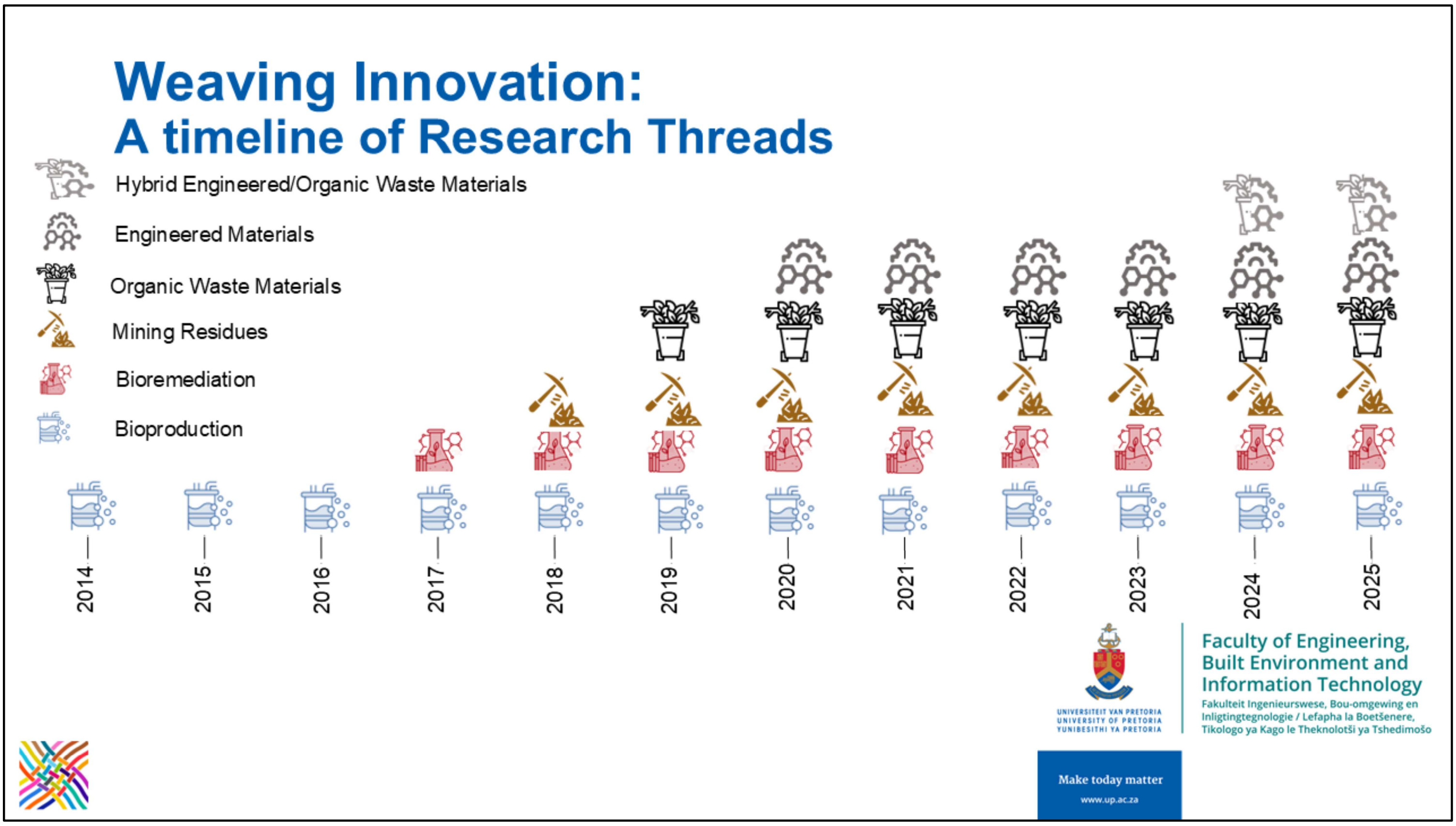
- "This diagram, developed by the Ellen MacArthur Foundation, beautifully captures the vision of a circular economy. It's called the *butterfly diagram*, and it illustrates two key loops: the biological and the technical cycles."

- **Biological Cycle (left wing)**
- "On the left, we have the *biological cycle*, where materials like food waste and other organics are cascaded and returned safely to nature through processes like composting, anaerobic digestion, or bioremediation. These processes regenerate natural systems."
- "This is where much of my group's work on bio-based remediation and microbial processes fits in—turning pollutants into something beneficial, closing loops that were once only linear."

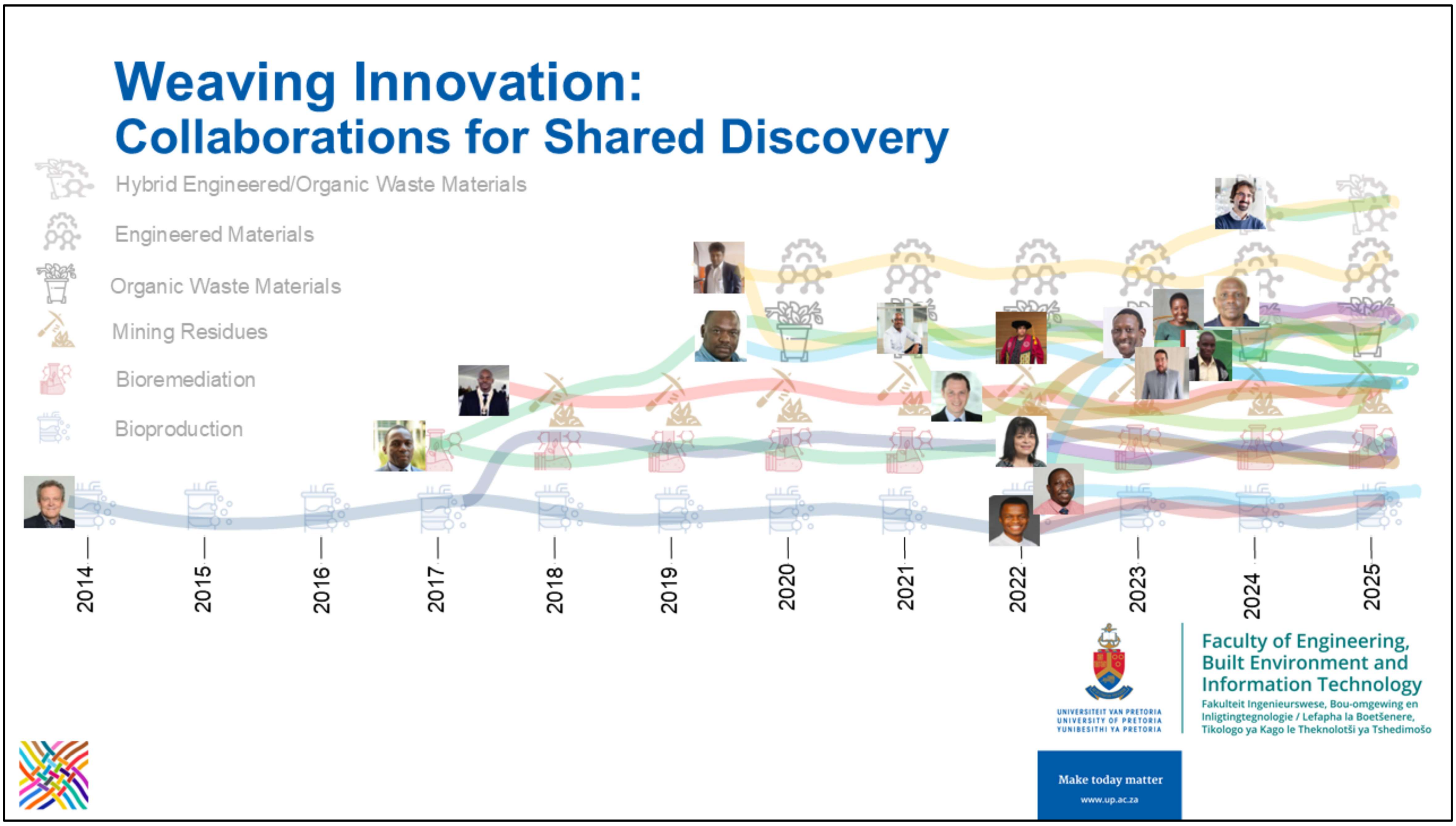
- **Technical Cycle (right wing)**
- "On the right is the *technical cycle*, which is all about keeping products and materials in use for as long as possible—through reuse, repair, refurbishment, remanufacturing, and finally recycling."
- "Our work on engineered materials, hybrid adsorbents, and recovery systems feed into this loop—offering new life to waste, rather than relegating it to landfill."

- **A Golden Thread through Both Loops**
- "Whether it's microbial, mineral, or material—our research has a role to play in both wings of this butterfly. The golden thread is the idea that **waste can be more than what it seems—it can become opportunity, value, even innovation**."

- So, where does all of this fit in globally?
- I believe it's crucial that our research doesn't just live in the lab—it must also speak to the **world's grand challenges**.
- That's why much of my work aligns closely with three Sustainable Development Goals:
  - **SDG 6 – Clean Water and Sanitation**
    Through bioremediation, pollutant removal, and acid mine drainage treatment, we target clean water not as a luxury, but as a right.
  - **SDG 9 – Industry, Innovation and Infrastructure**
    By developing advanced materials and upcycling industrial waste, we drive sustainable industrial innovation—especially in under-served regions.
  - **SDG 12 – Responsible Consumption and Production**
    Whether it's circular process design or bio-based technologies, our goal is to build systems where waste is not an endpoint—but a new beginning.
- This is not theoretical. It's practical. Measurable. Impact-driven.

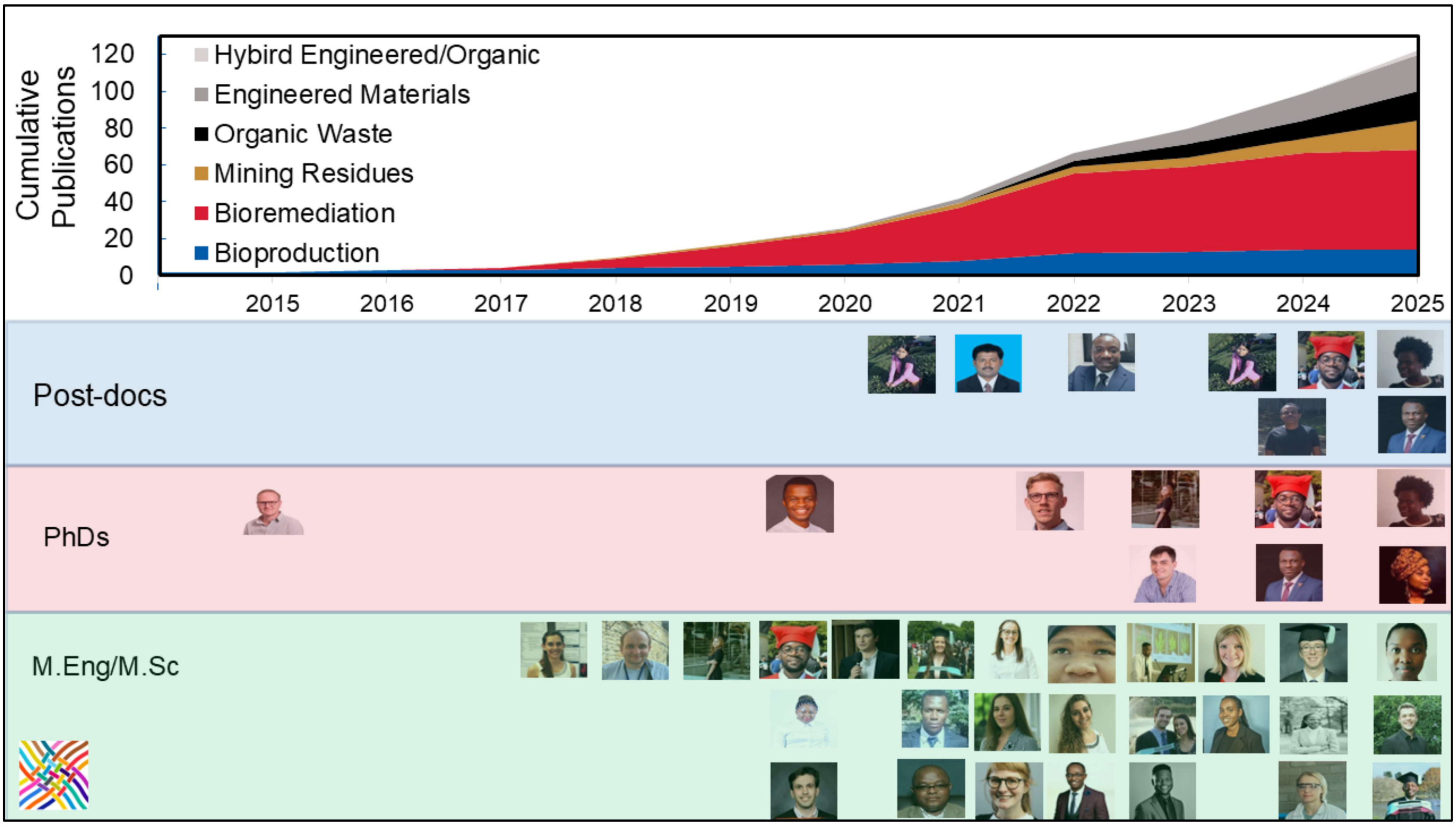


- "Here, you can see the evolution of my research over the last decade, visualised as threads in a woven pattern – each representing a different thematic strand of waste valorisation.
- We started in 2014 with a strong foundation in **bioproduction**. From there, we layered on **bioremediation** approaches in 2017, particularly using biological systems to treat wastewater and contaminated environments.
- By 2018, we expanded into **acid mine drainage residues** – taking what is often a hazardous industrial by-product and finding ways to repurpose it as a resource for water treatment or material synthesis.
- Around 2019, we began exploring **organic waste materials** – especially agricultural and food waste – not just for adsorption but for broader applications in circular systems.
- From 2020 onward, our work on **engineered materials** took centre stage: hybrid nanocomposites, functionalised polymers, and smart materials that go beyond passive adsorption.
- Most recently, we've seen an exciting convergence – where we combine organic and engineered systems into **hybrid composites** that are multifunctional, scalable, and closer to real-world application.
- Each of these threads builds on the last – reinforcing one another and forming a stronger, more integrated research tapestry. The goal was never to chase trendy topics, but to pursue a coherent vision: *how to close loops and recover value from waste.*"



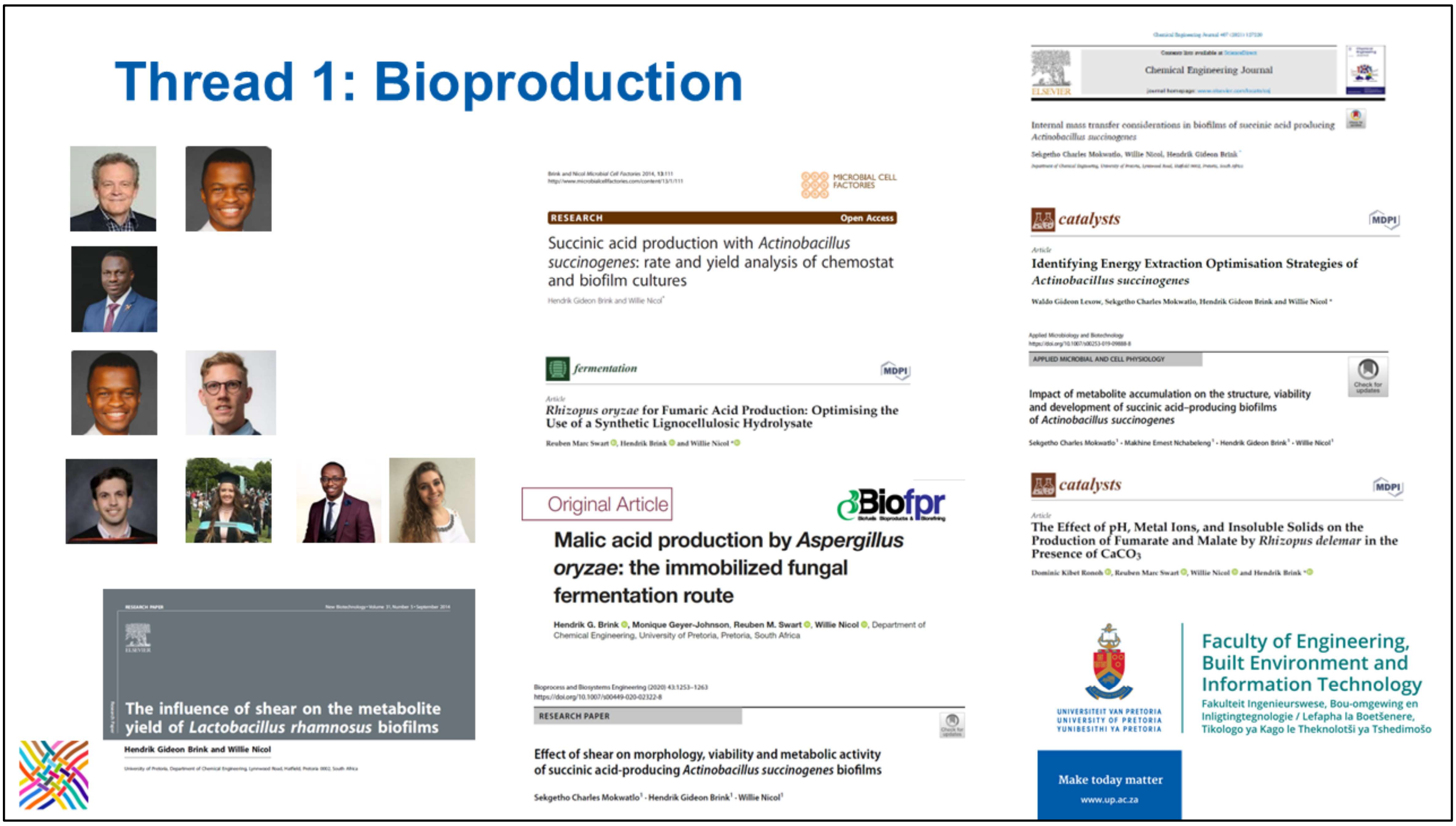
"Let me pause here to emphasise something critical about how this research evolved: I did not walk this path alone."

- This timeline isn't just about research outputs – it's a **tapestry of people**. Each thread you see here represents more than a project; it reflects the **trust, mentorship, and collaboration** that fuelled it.
- You'll recognise faces here: brilliant colleagues, students who became co-authors, mentors who nudged me forward, and new collaborators who challenged the status quo.
- Some of these relationships span nearly a decade – like my collaborations with **Prof Willie Nicol** (my PhD supervisor) **and Prof Evans Chirwa**, which deeply shaped our bioremediation work.
- Others are more recent but just as impactful – such as our exciting interdisciplinary links with **biosensor teams** and **international partners** from Switzerland, Austria, and Uganda.
- What this slide truly shows is how research **intersects with people**. The most innovative science often emerges not from isolation, but from these shared spaces of curiosity and respect.
- Together, we navigated the complexity of AMD residues, engineered materials, organic waste valorisation, and more – building not just knowledge, but capacity and community.
- I'm deeply grateful to each person on this slide. You didn't just contribute – you **co-created** this journey.

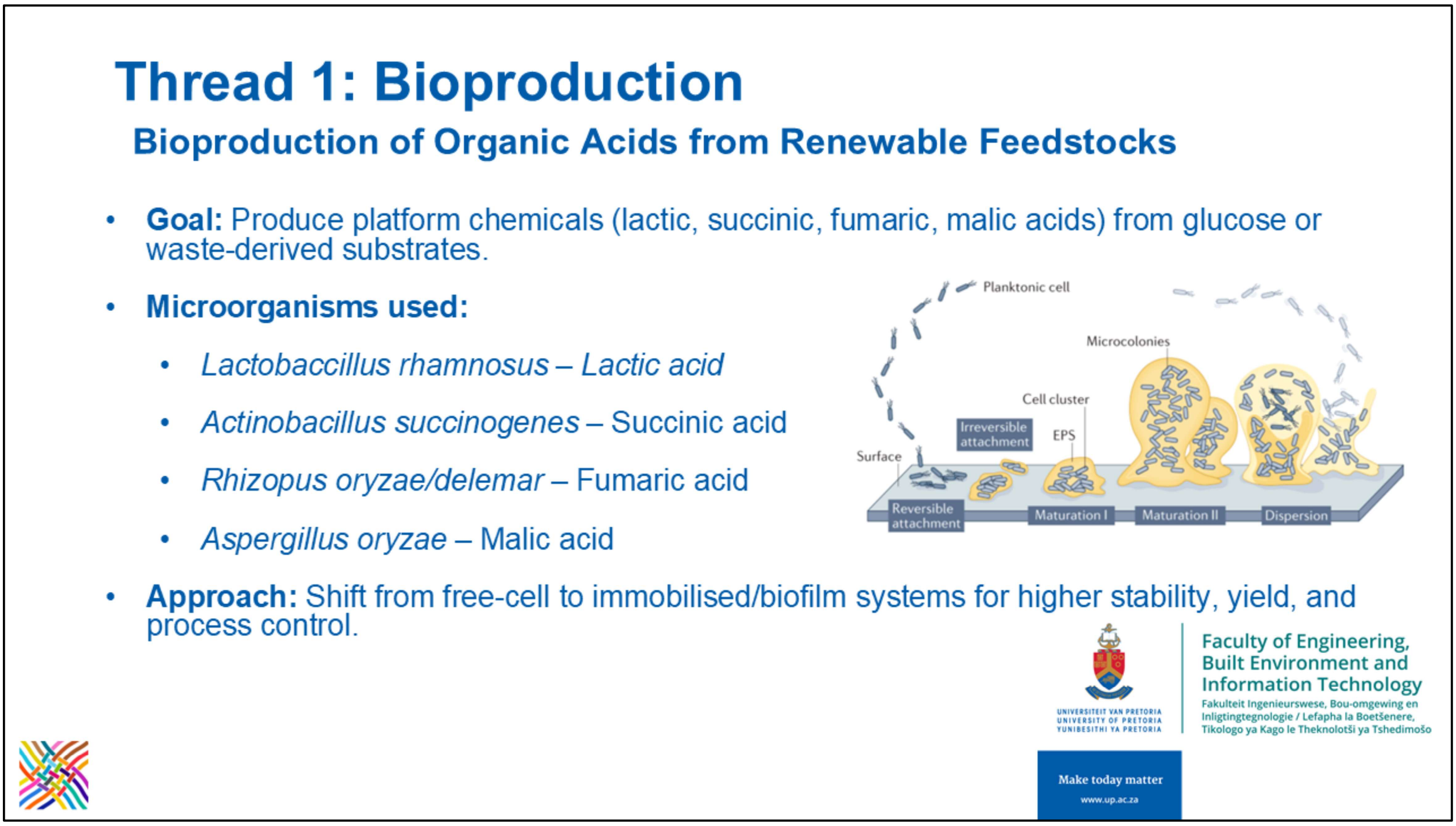


Before we delve into the individual strands of research, I want to acknowledge the engine behind it all: our people.

- At the top of this slide, you'll see the trajectory of our cumulative research output across six thematic areas — each colour representing a thread that has grown and evolved over time. But what truly matters is what lies underneath that curve.
- These are the faces behind the work — the postdocs, PhDs, and master's students who have poured themselves into solving the challenges that underpin each of those research strands.
- This is not just a body of work; it is a *community of practice*. One that has matured organically, from papers with only myself and my PhD supervisor in 2014, to multidisciplinary collaborations, and from early MEng efforts to high-impact PhD and postdoc leadership.
- Every publication you see here is the product of shared discovery. And as we move through the next section, exploring each thread — from bioproduction to hybrid-engineered materials — remember: the science was only made possible because of the people who believed in its purpose.



- “The first research thread I’d like to highlight is **Bioproduction**, where we explored microbial production of high-value organic acids and metabolites.”
- “This body of work wouldn’t have been possible without the contributions of the brilliant researchers you see on the left – including [point to photos] collaborators, postdocs, PhD students, and master’s students who brought passion, rigour, and creativity to the lab.”
- “Some of the **most prominent outputs** from this thread are featured here demonstrating the academic impact of the work completed”
- “The technical story behind these will follow in the next few slides – but what you’re seeing here is the fabric of a research thread woven by people and purpose.”



"Our focus has been the bioproduction of organic acids from renewable feedstocks – particularly platform organic acids like lactic, succinic, fumaric, and malic acid. These are not fringe molecules. These are core building blocks for a sustainable bioeconomy."
"Each of these acids plays a crucial role in enabling green chemistry pathways:

- ***Lactic acid produced by Lactobaccilus rhamnosus** is the monomer for PLA, a leading biodegradable plastic.*
- ***Succinic acid produced by Actinobaccilus succinogenes** is a precursor for biodegradable polyesters like PBS.*
- ***Fumaric from Rhizopus delemar** and **malic acid from Aspergillus oryzae** serve diverse roles – from food additives to pharmaceutical precursors and specialty chemicals."*

*"So why are we doing this? Because these platform chemicals allow us to reimagine fossil-based routes using biological systems and waste carbon sources – anchoring both **green material production** and **biobased chemical industries**."*

But it's not just about the microbe—it's about the **form** in which they grow. We moved away from conventional free-cell cultures to **immobilised systems and biofilms**. These systems give us higher **stability**, **yield**, and **control**—a bit like building a more disciplined microbial factory.

- The graphic shows the different stages of biofilm formation—from planktonic cells to mature, structured colonies. It's in this structured community that these organisms thrive under industrial conditions.

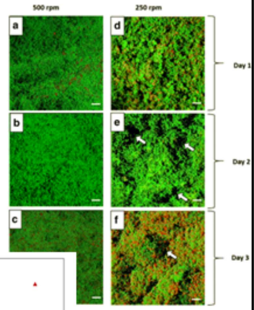
- This thread laid the **biochemical foundation** for several other directions that followed—including bioremediation and green materials—making it a key stepping stone in the broader pattern of waste valorisation.

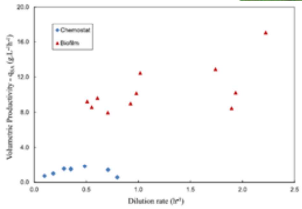
Thread 1: Bioproduction

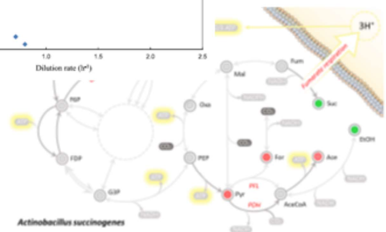
Bioproduction of Organic Acids from Renewable Feedstocks

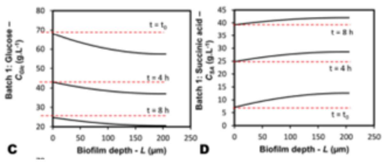
Highlights:

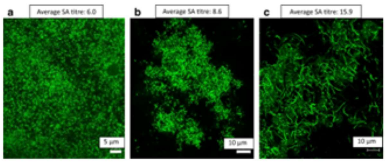
- **Succinic acid** (*A. succinogenes*):
  - Biofilm increases tolerance and improves yield.
  - Mass transfer and metabolite accumulation.
  - Pathway analysis to enhanced energy recovery.











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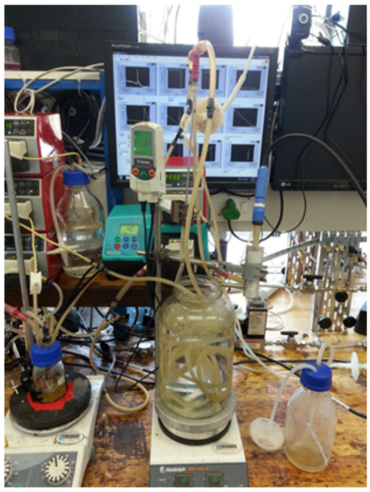
- "Now let's dive into one of the most productive research strands: **the bio-based production of succinic acid** using *Actinobacillus succinogenes*.
- 🔬 In this project **Biofilm reactors** became a major turning point in our approach. We discovered that transitioning from traditional free-cell systems to **immobilised biofilms** dramatically increased tolerance to shear forces and boosted product yields.
- However, this wasn't without complexity. We found that **internal mass transfer limitations** within the biofilm and **metabolite accumulation** became critical bottlenecks in performance. These became focal points in our optimisation efforts.
- Using a combination of metabolic and pathway analysis, we were able to reveal **strategies for improved energy recovery**, pushing the system toward more sustainable and cost-effective production.
- It's not just about growing bugs—it's about **engineering nature to meet industrial needs sustainably**."

Thread 1: Bioproduction

Bioproduction of Organic Acids from Renewable Feedstocks

Highlights:

- **Lactic acid (*L. rhamnosus*)**
  - **Silicone tubing-based biofilm reactor**
  - **Shear rate had a significant impact**
  - Achieved a **maximum lactic acid yield of 0.88 g/g glucose**



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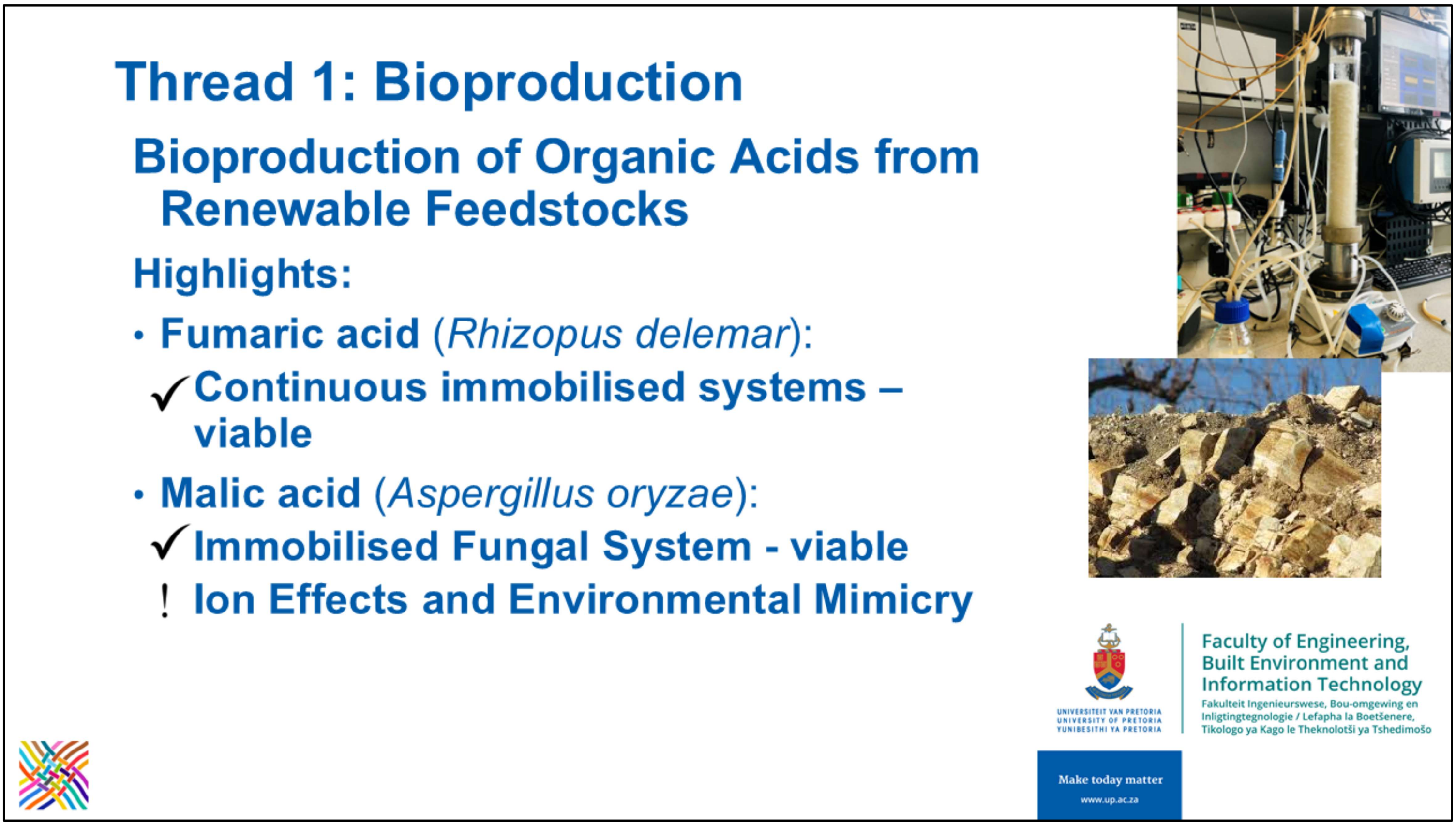
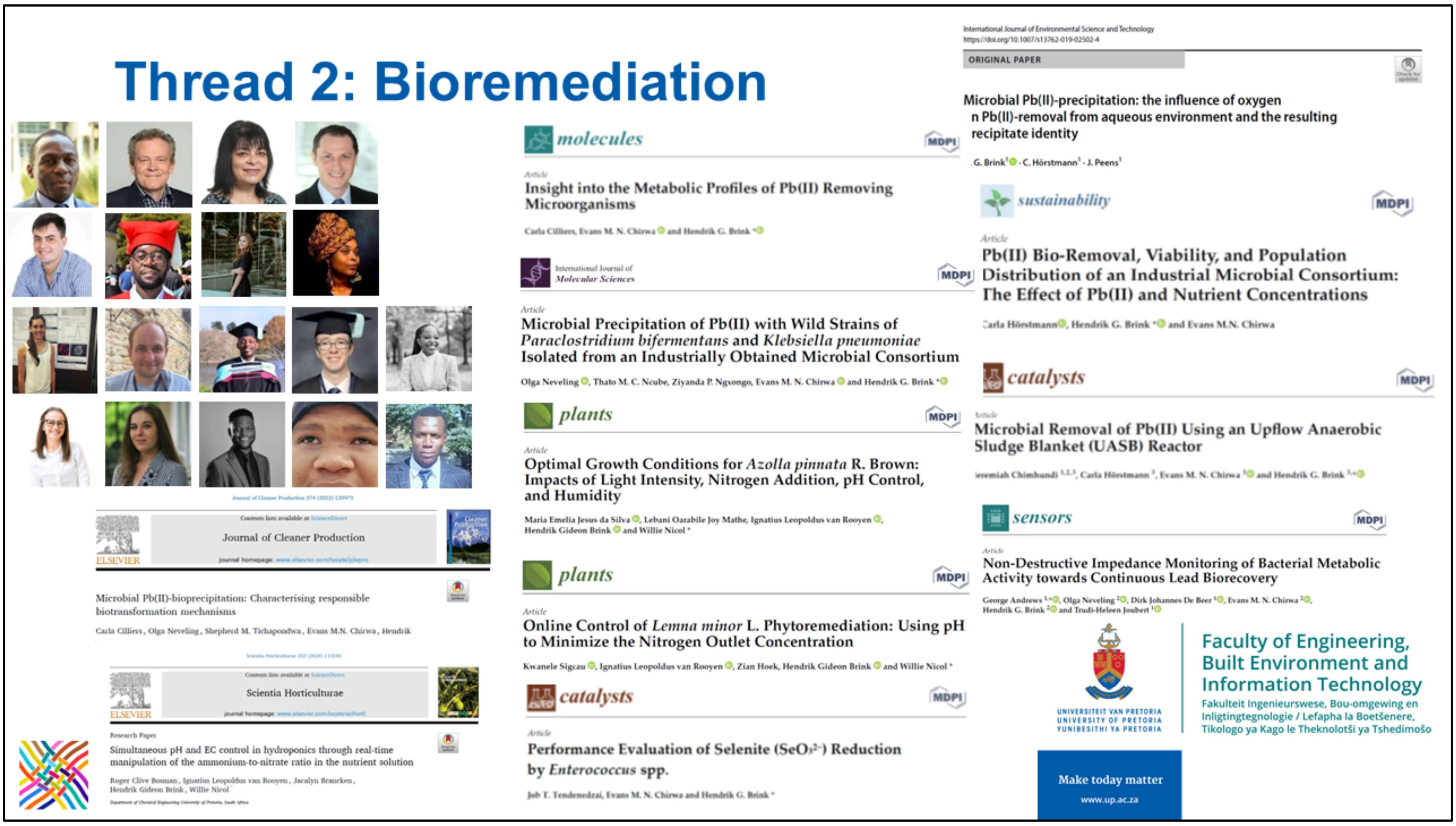
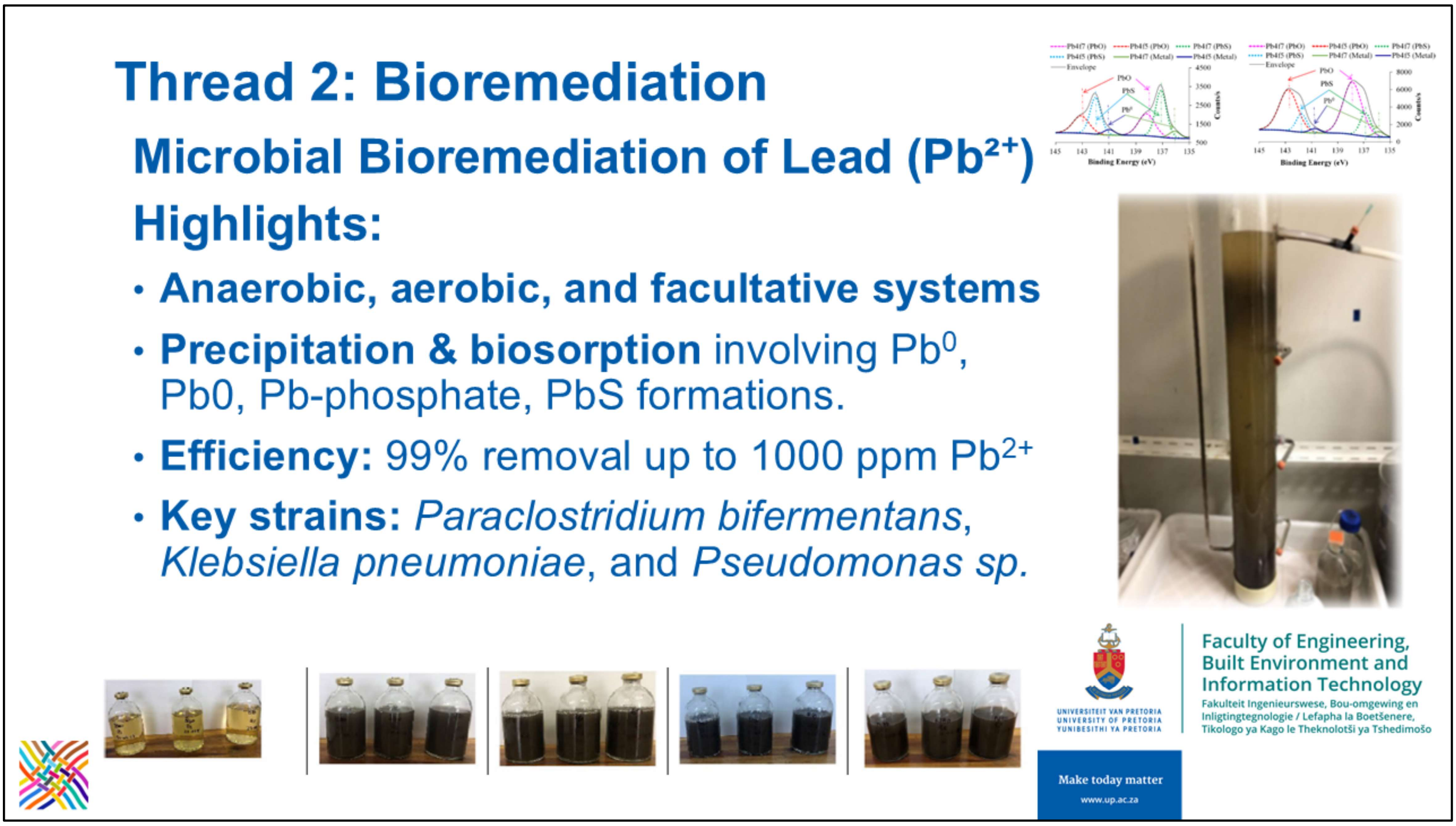
- "Now let's turn our attention to *lactic acid production*, a cornerstone of our bioproduction research.
- We developed a **silicone tubing-based biofilm reactor** – simple in design, but highly effective. This allowed us to run stable, continuous production under controlled pH conditions, which is crucial for downstream separation and industrial viability.
- One of the most interesting findings was how **shear rate** affected productivity.
  - At moderate levels, shear actually **boosted metabolite yield**.
  - But too much shear? It **disrupted the biofilm**, leading to detachment and a sharp drop in productivity.
- We achieved a **maximum yield of 0.88 grams of lactic acid per gram of glucose**, which is remarkably efficient – putting us in the range of what's needed for industrial-scale bio-based chemical production.



- "Continuing with the bioproduction thread, we zoom in on two more key platform chemicals: **fumaric acid** and **malic acid**.
- Let's start with **fumaric acid**, produced using *Rhizopus delemar*. We demonstrated that continuous immobilised systems were not only viable but actually performed well using either glucose or mixed sugars like glucose and xylose—this mimics real lignocellulosic biomass feedstocks, making the system relevant to industrial waste valorisation.
- For **malic acid**, we turned to *Aspergillus oryzae*. Our approach used a PVC support matrix for immobilisation, which provided stable growth under controlled conditions.
- A particularly interesting finding here was how **ion effects mimic environmental cues**: adding calcium carbonate ($CaCO_3$) was required for malic acid production, likely by recreating the fungus's natural calcareous habitat. Conversely, **sodium ions** inhibited glucose uptake—a clear red flag for systems exposed to saline conditions or brines. This shows the importance of matching reactor conditions to the biology of the organism.

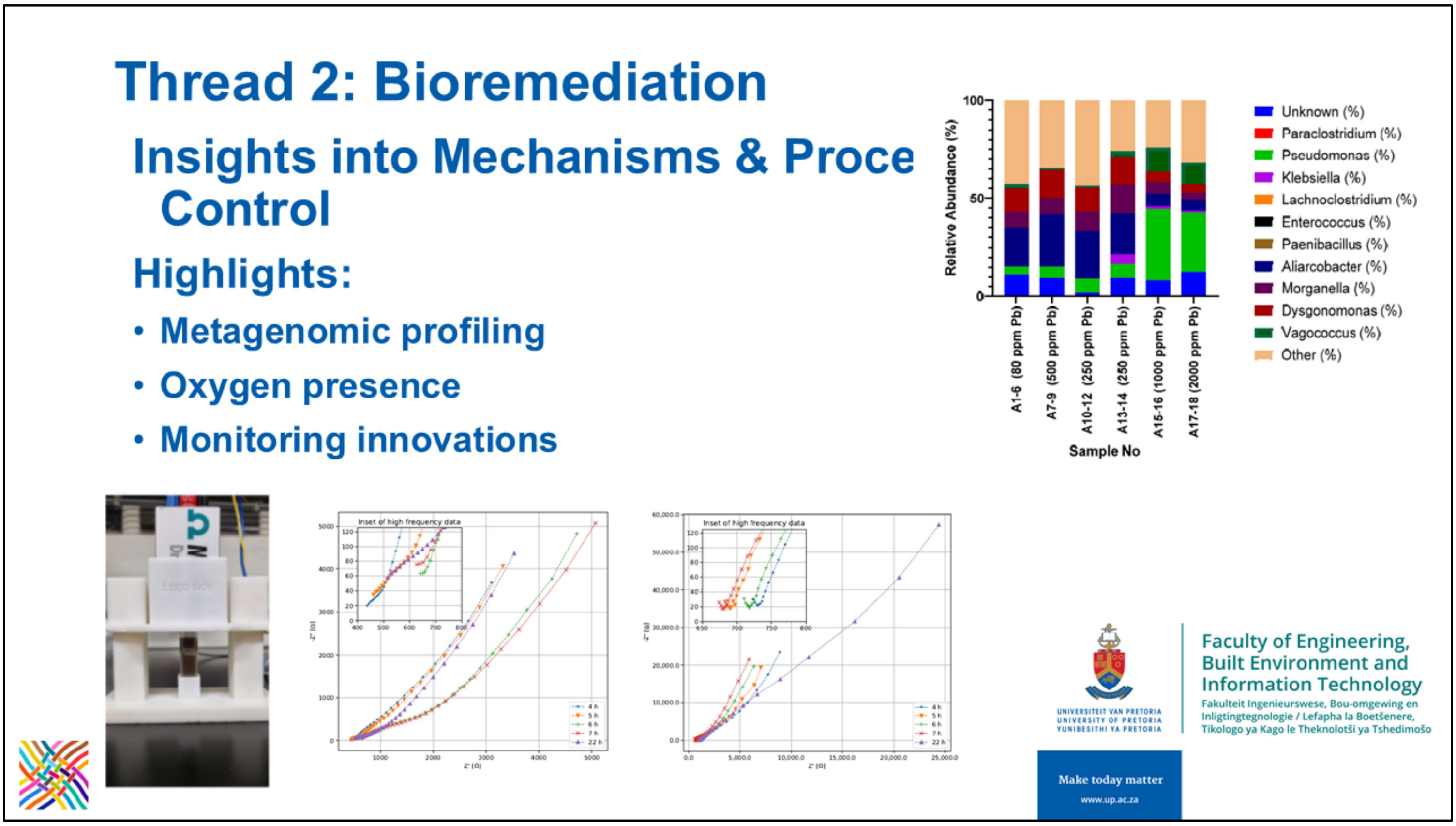


- “Let’s move to **Thread 2: Bioremediation** – a strand deeply rooted in nature-based solutions and systems thinking.”
- “This thread would not exist without the efforts of an incredible group of collaborators – many of whom are shown here. You’ll recognise faces from both South Africa and abroad, ranging from long-time colleagues to new students who’ve brought energy and curiosity into the lab.”
- “Our bioremediation research has produced a robust body of work – from microbial lead precipitation and phytoremediation to the use of Azolla, Lemna, and even advanced electrochemical sensing systems for microbial activity. These outputs span a wide range of journals, illustrating both the technical and biological dimensions of our work.”
- “At its core, this thread reflects a belief that polluted environments can be rehabilitated not only with chemistry, but through the **synergistic potential of life itself** – microbes, plants, and engineered consortia working together.”



- “This first project focuses on the **biological removal of heavy metals**, particularly lead, from contaminated water systems.
- We explored a variety of microbial systems – **aerobic, anaerobic, and facultative** – using both mixed and pure cultures. Our goal was to identify which microbial communities are most effective under different redox conditions.
- The results showed that **precipitation and biosorption** were the key mechanisms driving lead removal. Depending on the microbe and conditions, we saw the formation of PbS, PbO, Pb-phosphate, and even elemental lead – all of which reduce bioavailability and toxicity.
- Three strains in particular stood out for their high tolerance and performance:
    - **Paraclostridium bifermentans**
    - **Klebsiella pneumoniae**
    - **Pseudomonas species**
- These were able to tolerate lead concentrations above **1000 ppm**, and still achieved **removal efficiencies close to 99%** – and importantly, this was seen in both **batch systems and continuous systems**, such as the **UASB reactor** shown here.

This work has significant implications for **low-cost, decentralised wastewater treatment**, particularly in mining-impacted areas where lead contamination remains a serious concern.”



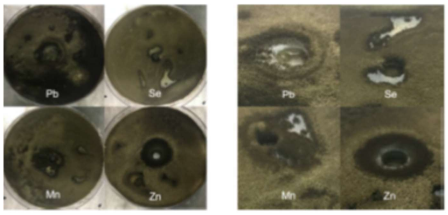
- We dug deeper into *how* bioremediation of lead works—and how to optimise it.
- Specifically:
  - **Metagenomic profiling** showed that the culture adapt under Pb stress by changing the metagenomic profiles—i.e. the collective distribution of the organisms present in the system—indicating biochemical stress responses linked to Pb removal.
  - **Oxygen levels** played a key role in determining which Pb species formed and which microbes dominated—giving us a control handle for steering bioprecipitation.
  - **Real-time monitoring** with impedance biosensors let us track microbial activity live—opening doors for dynamic, controlled bioremediation processes.

Thread 2: Bioremediation

Expanding the Toolkit – Plants, Consortia, and Control

Highlights:

- **Phytoremediation** with *Lemna minor* and *Azolla pinnata*
- **Mycoremediation** with Aspergillus spp



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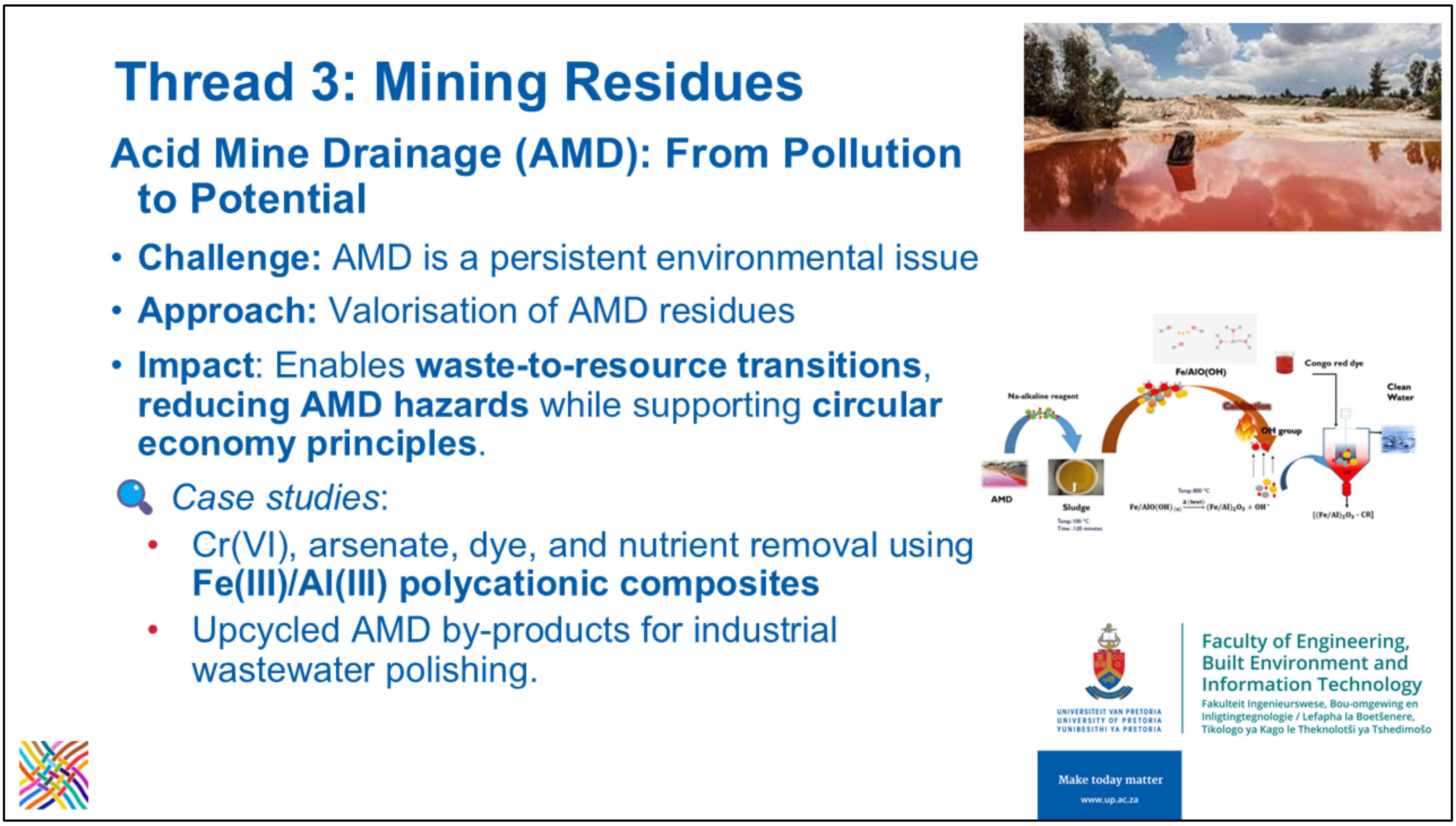
- “So, stepping a bit outside the petri dish, we started looking at nature’s engineers—plants and fungi—as allies in remediation.”

- *“For phytoremediation we trialled species like **Lemna minor** and **Azolla pinnata**, which are small aquatic plants, to polish wastewater”*
- *“They respond to nitrogen and pH changes, making them perfect natural sensors and filters—cost-effective and easy to manage.”*

- *On the fungal side, **Aspergillus** strains showed real promise. They didn’t just survive post-treatment conditions—they tackled heavy metals and degraded residual pollutants.”*
- *“Think of this as extending the treatment train: microbe to plant to fungus.”*

- “These systems push us toward **biological redundancy**, where no single species carries the load. It's robust, elegant—and frankly, a little bit bohemian.” *(smiles)*

- Right, now let’s talk about a thread that really captures what I like to call my *“hippy engineer”* side — working with what others see as waste, and reimagining it into something valuable.
- This thread focuses on **Mining residues** — those nasty, acidic leftovers from mining activities. And yet, when we looked closer, we saw potential.
- And as with all these threads, this work wasn’t done alone. These are some of the **faces behind the journey** — collaborators, postdocs, master’s students — each one bringing their own perspective to a messy, complex challenge.
- The right of the slide shows some of the publications emanating from this work demonstrating the impact and importance of the work done.



- The first mining residue we looked at was acid mine drainage residue
- Firstly lets ask ourselves, " What is **acid mine drainage**, or AMD"?.
- 💬 *"If you've ever seen those bright orange or red pools around old mining areas—this is it. AMD is like the ghost of mining past, but we're trying to give it a future."*

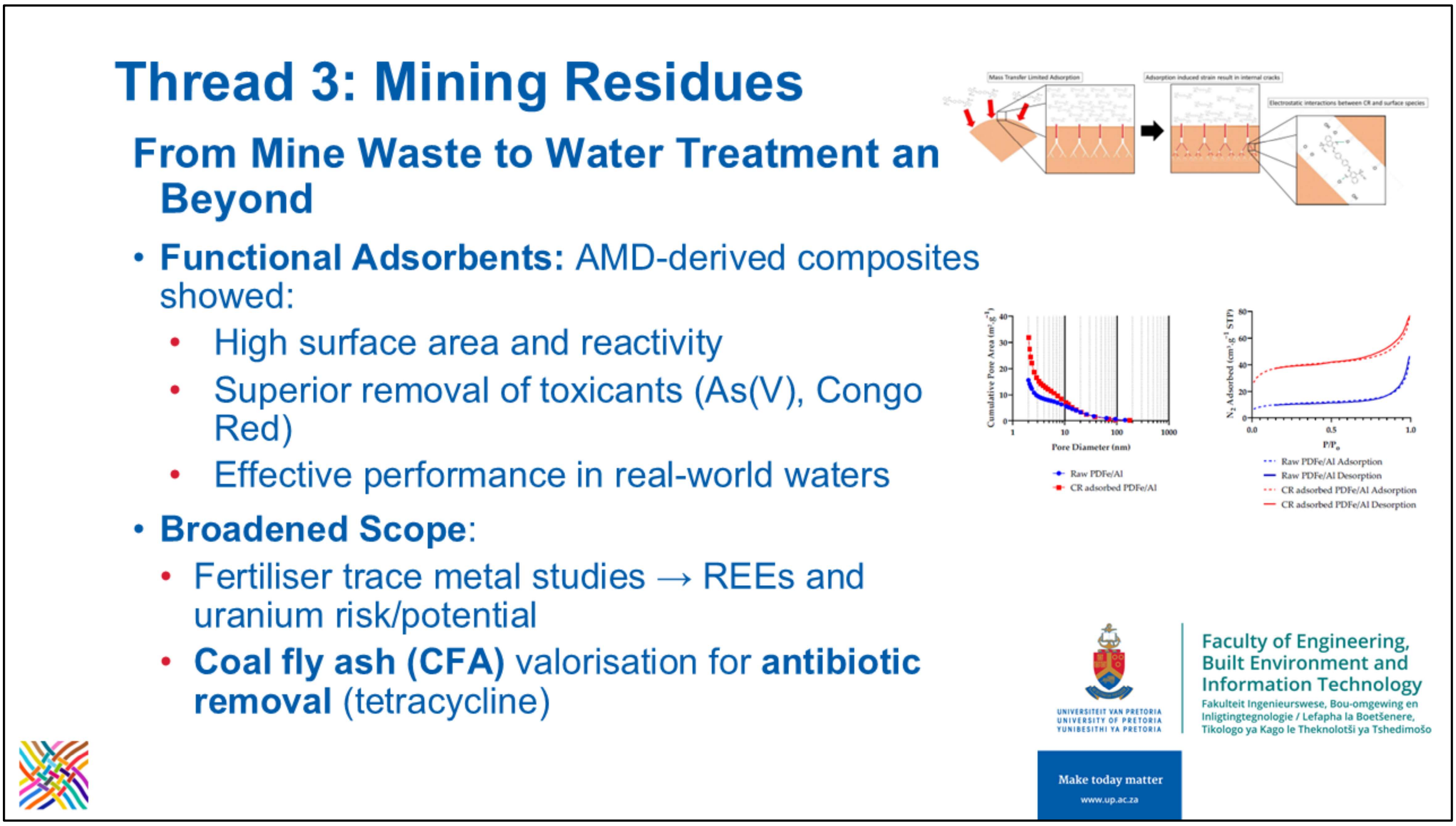
- 🔍 **Challenge**
  AMD is a **persistent environmental threat**, rich in **iron, aluminium**, and all kinds of trace elements—*the good, the bad, and the toxic.* We're talking **rare earths**, **uranium**, **chromium(VI)**—high risk, but also high value.

- 🔁 **Our Approach**
  We treat AMD not as waste, but as **resource-rich sludge**.
  We extract value through, **Metal recovery, Synthesis of functional nanocomposites, and Reusing residues for water treatment**
- It is waste valorisation in action—aligned with circular economy thinking.

- 🌍 **Why It Matters**
  This research is all about enabling a **waste-to-resource transition**.
  By repurposing AMD residues, we're reducing environmental risks *and* producing useful materials for broader water treatment applications.

- 📌 **A few case highlights:**
- We've used **Fe/Al nanocomposites** to remove **Cr(VI)**, **arsenate**, dyes, and nutrients.
- We've **upcycled AMD treatment by-products** to polish industrial wastewater—

extending the life of these materials *and* improving water quality.

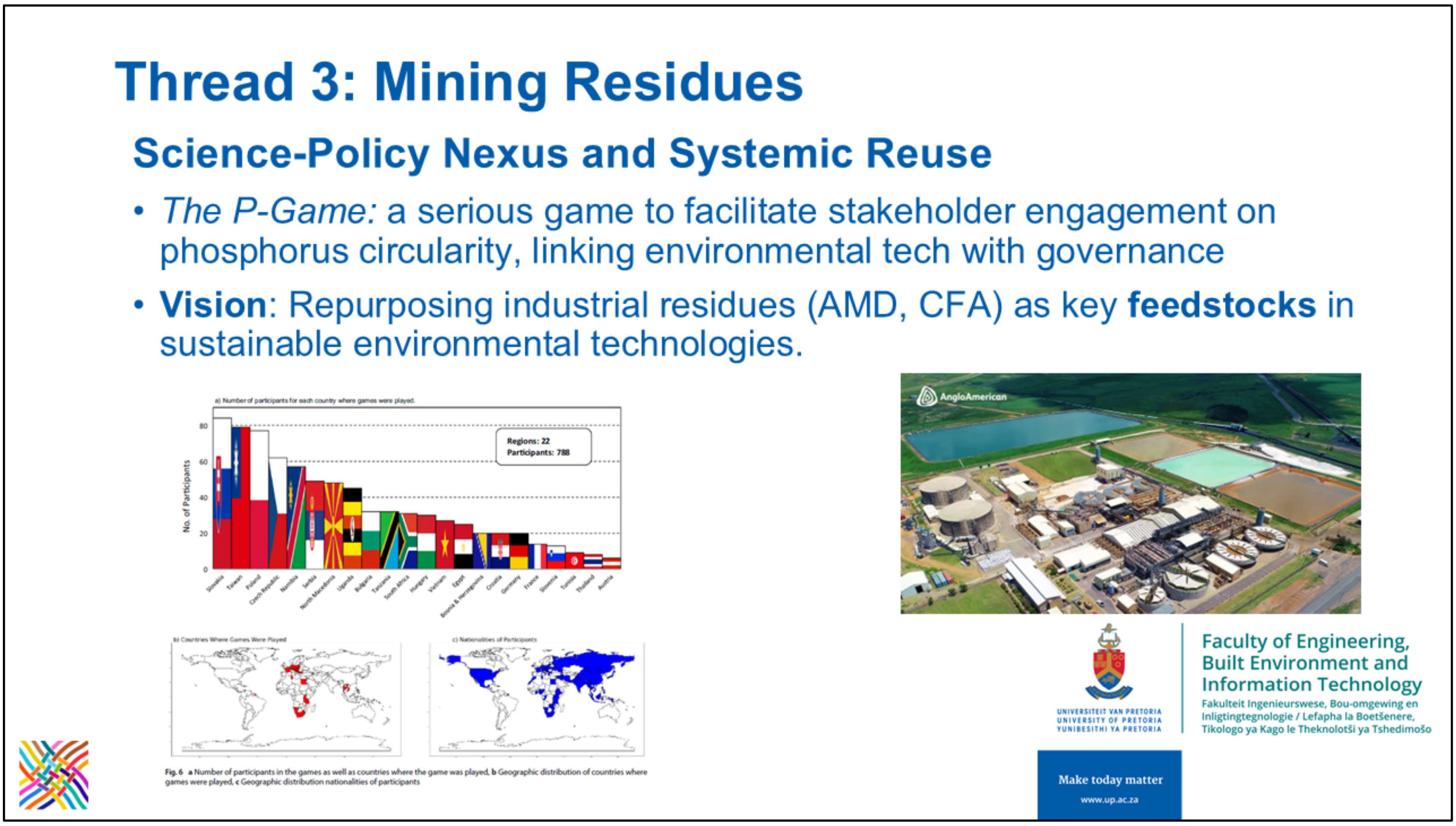


- The results from the applications demonstrated that the developed **functional adsorbents** has:
  - high surface area and reactivity.
  - These materials didn't just look promising in the lab — they actually showed **superior removal** of nasty stuff like arsenate and dyes like Congo Red,
  - even in real-world waters.

But it didn't stop there.

- We broadened the scope — looking at **fertiliser** for instance. Turns out, trace metals like REEs and uranium may be present, posing both risk and opportunity. That opened a whole new layer of inquiry.
- And we also valorised **coal fly ash** — a legacy waste stream from power generation — for the removal of **antibiotics like tetracycline**. This tied together multiple strands: mining, energy, water, and health.

So again, the core idea is consistent: waste can be more than a problem. With a bit of imagination and some good chemistry, it can become a solution.



- So, as our understanding of mining residues deepened, something else became clear:

- 🔚 It's not just about cleaning up the mess. It's about **changing the system** that creates it.

- We realised that if we want real impact, the science needs to connect with **policy, governance, and stakeholder awareness**.

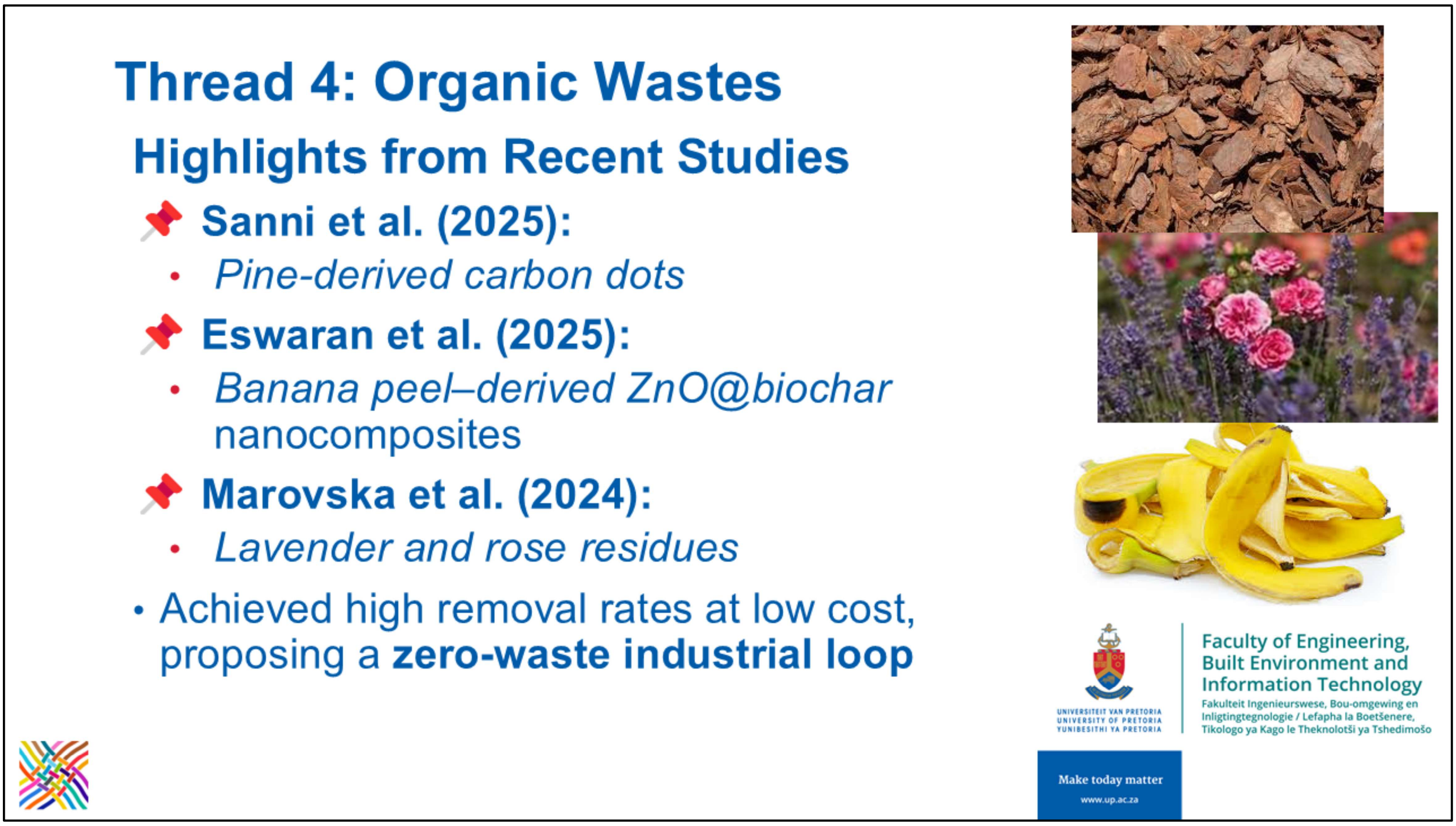
- 🧠 **The P-Game** became one of our tools for that.
  It's a serious game — yes, a game — that helps stakeholders explore phosphorus circularity. It breaks down complex systems and helps participants link science with governance in a way that's engaging and constructive.
- This game has been played by 788 participants in 22 regions so far – demonstrating the international impact of the project

- 🌍 And our **vision** grew:
  Why not repurpose these mining residues — not just AMD, but also coal fly ash — as **strategic feedstocks** for sustainable environmental tech?

- It's about shifting mindsets:
  From waste to resource.
  From clean-up to circularity.
  From reaction to prevention.
- And in this space between science and policy, we find powerful leverage points for change.

- And now we move to *Thread 4* — Organic Wastes.
  This slide is really about acknowledging the people and the publications behind this body of work.
- You'll see many familiar faces here — students, postdocs, and collaborators who've worked across different aspects of organic waste valorisation.
- And on the right — just a glimpse of the publication output this thread has generated. From catalytic applications and solar desalination innovations to carbon nanomaterials and adsorption studies — the breadth is impressive.
- These are the people and papers that laid the foundation. I'll walk you through the work itself in the next few slides.

- Right — so with that incredible team and the growing body of work in mind, let's unpack what Thread 4 is really about.
- This thread dives into **circular approaches using organic waste materials** — things like eggshells, bark, banana peels, rose and lavender waste, spent microbial biomass and even waste automotive tyres. It's classic *waste-to-resource* thinking: transforming agricultural and food by-products into high-value materials for water treatment.
- We've looked at all sorts of technologies here — **adsorption, photocatalysis, fluorescence sensing**, and even **nanocomposite synthesis** — all aimed at sustainable pollutant removal.
- And this work has real impact. It touches on **multiple SDGs** — from clean water to responsible consumption — and it pushes us toward greener chemistry and circularity, not as buzzwords, but as practical strategies.
- We'll break down the materials and findings next — but it all starts with that core philosophy: *waste isn't waste until you waste it*.



- Right, so let's dive into what we've actually *done* in this thread on organic wastes.
- You've already seen the people and publications — a wonderful mix of students and collaborators who really brought the creativity here.
- Now, here's what their work delivered:

- 🔬 **Sanni et al. (2025):**
  We started simple — *pine-derived carbon dots* used as fluorescent sensors. These could pick up antibiotics like amoxicillin and tetracycline — a clever, low-cost detection strategy for polluted water.

- 🌱 **Eswaran et al. (2025):**
  Then we got into *banana peels*. Yes — banana peel–derived **ZnO@biochar** composites that removed over 95% of methylene blue.
  What's great is that this wasn't just about adsorption — it linked waste valorisation with **solar photocatalysis**, pushing toward low-energy, decentralised water treatment.

- 🌷 **Marovska et al. (2024):**
  And finally, a more aromatic touch — *lavender* and *rose* residues were used to adsorb **Acid Orange 7 dye**, achieving high removal rates even at low cost.
  This work made the case for **zero-waste water treatment loops**, proposing that by-products from one process can close the loop in another.

- In each case, it's the same logic: **Use what we have — wastes, residues, by-products — and turn them into materials that solve real environmental problems.** And I think that's a beautiful, scalable idea.

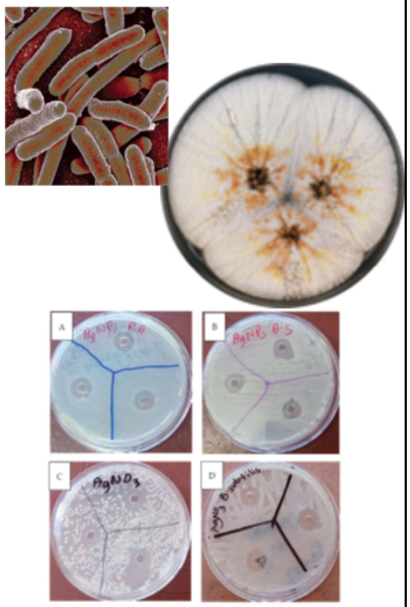
Thread 4: Organic Wastes

Advanced Biosorbents and Mechanistic Insights

📌 **Brink et al. (2024) & Kpai et al. (2023):**
- **Inhibited bacterial cultures**
- **Mechanistic modelling**

📌 **de Wet & Brink (2021):**
- *Aspergillus piperis*
- Promising fungal alternative

📌 **Aina et al. (2023):**
- *Eggshell membrane & AgNPs hybrid material*
- Demonstrates **hybrid synergy** between bio-waste and nanotechnology



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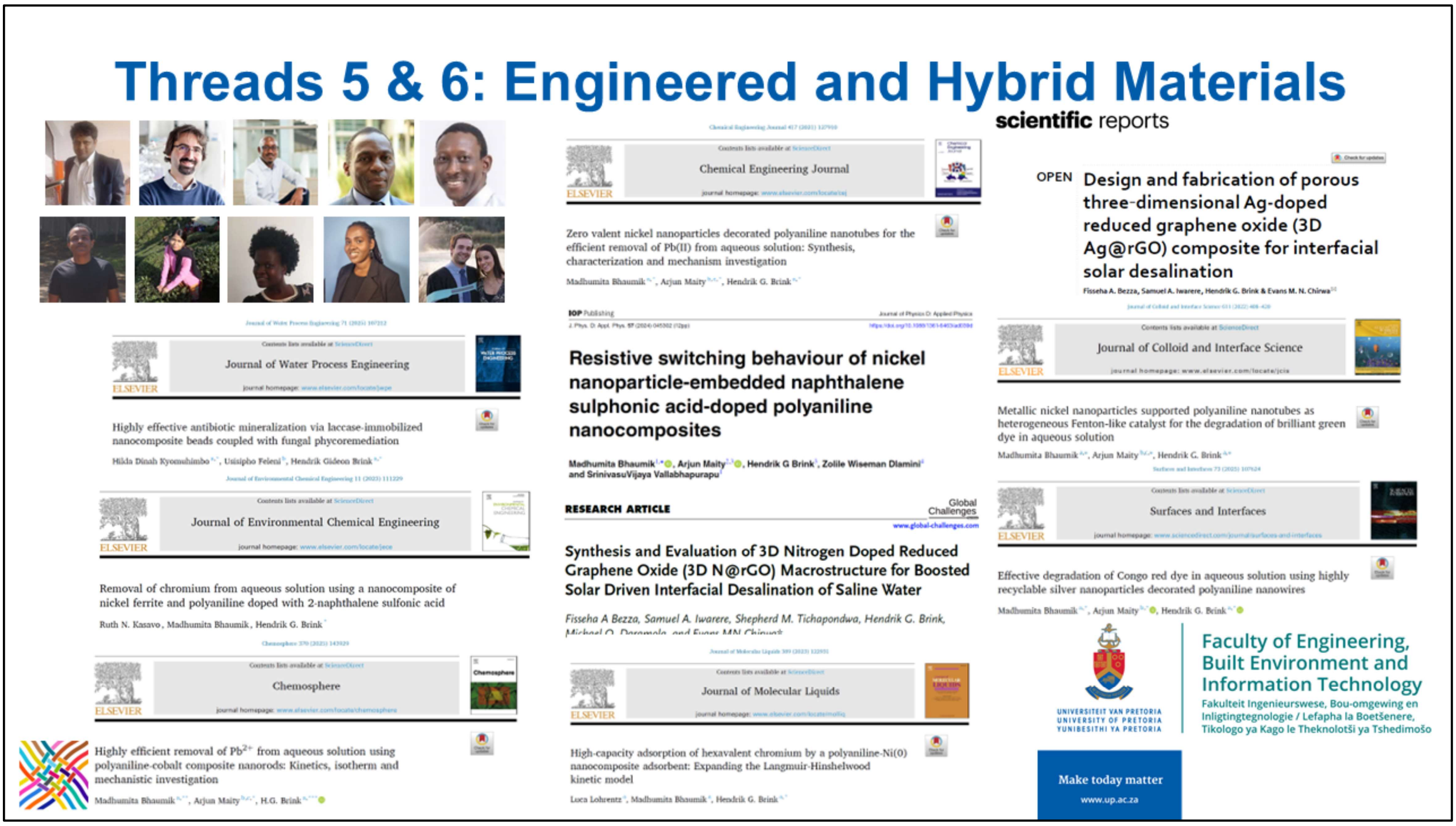
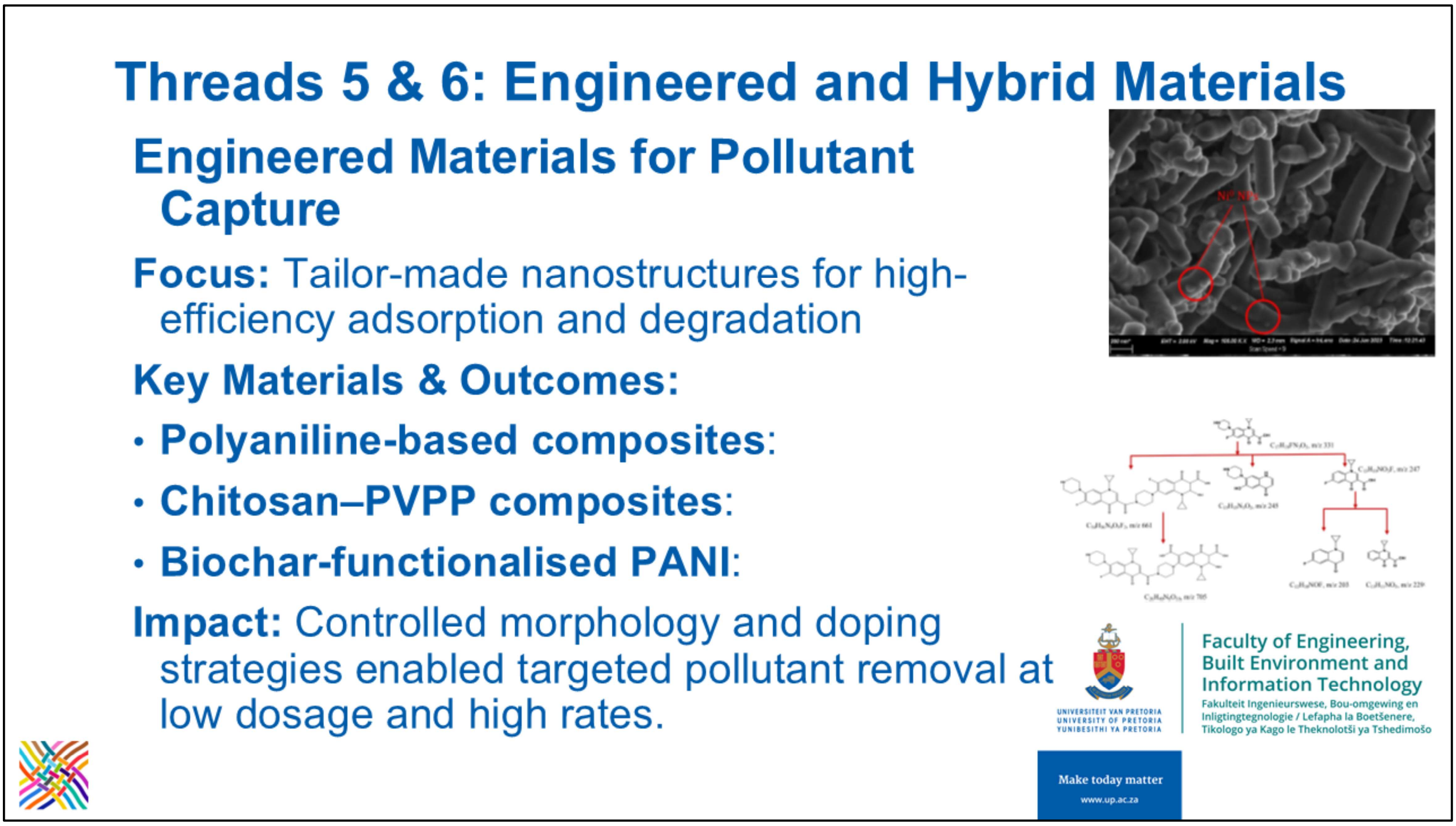
- Right, let’s wrap up Thread 4 with some deeper insights into the **biosorbents** we’ve been developing from organic wastes – and the mechanisms that make them tick.
- 💡 **Brink et al. (2024)** and **Kpai et al. (2023)** led studies showing how bio-waste–derived materials can inhibit bacterial growth while still offering high Pb(II) removal. We didn’t stop at performance testing — we used **mechanistic modelling** to validate how these materials interact at the surface level and when they reach saturation. This helps us move from trial-and-error to rational design.
- 🍄 **de Wet & Brink (2021)** explored fungi, particularly *Aspergillus piperis*, for lead biosorption. The uptake was fast, stable, and surprisingly effective — hinting at how biological systems can offer industrially relevant alternatives.
- 🧪 Then, in **Aina et al. (2023)**, we combined **eggshell membranes** with **silver nanoparticles** — creating a composite material that tackled both pathogens and heavy metals. This is where **bio-waste** and **nanotech** start to really merge into something powerful.
- In all of these, we’re pushing beyond just *does it work?* to *why it works, how it works, and how we can improve it*.
That’s the heart of our mechanistic approach: understanding the fundamentals so we can scale responsibly and sustainably.



- **And finally, we arrive at Threads 5 and 6—where the creativity of our collaborations really comes into focus."**
- 👥 *[Gesture to slide]*
  "These faces represent cross-disciplinary work—material scientists, physicists, engineers, and chemists—converging to push boundaries in advanced environmental technologies."
- 📚 "The range of publications here tells the story: from smart materials and nanocomposites to hybrid adsorbents and engineered catalysts, it's a convergence of disciplines and ideas."
- **"This is where we asked: What happens when we stop choosing between nature-based and synthetic solutions—and start combining the best of both?"**
- *And in many ways, it's the natural endpoint of all the previous threads: science that doesn't just solve problems, but reshapes the possibilities."*



- Alright, now let's talk about some of the **tailor-made materials** we've been developing—where we take engineering precision and aim it squarely at pollution.

- 🧪 **What's the goal here?**
It's all about creating **engineered structures** with high surface area, selectivity, and reactivity—so they can capture or break down pollutants efficiently, even at low concentrations.
- Let's break down a few key materials:

- 🔴 **Polyaniline-based composites**
We've worked with doped polyaniline—specifically PANI-NSA structures—and even decorated it with metals like **Ni(0)**, **CoO**, and **Ag nanoparticles**.
These materials showed **exceptional removal** of **Pb(II)** and **Cr(VI)**.
And what's more, by tweaking the doping and morphology, we could actually tune the selectivity and uptake kinetics.

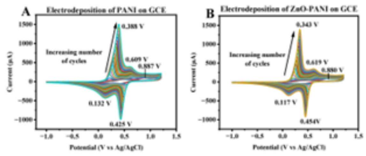
- 🟣 **Chitosan–PVPP composites**
This one came out of a fun collaboration—taking **biopolymer chitosan** and stabilising it with **PVPP foam**.
The result?
Super rapid **dye adsorption**, especially for things like methylene blue. This worked in both batch and continuous columns.
Plus, we got nice tunability in surface interactions, which hints at broader applications beyond just dyes.

- ⚫ **Biochar–functionalised PANI**
  Here we combined **waste-derived biochar** with conductive polymers.
  The hybrid had both **porosity and electron transfer properties**, giving a serious boost to **Cr(VI) adsorption**.
  So again, you see that **waste valorisation** thread, but now with engineered performance.

- 💡 **Why this matters**
  All these systems have one thing in common:
  They're designed with intent—**low dose, high speed, and real-world practicality**.
  We're not just chasing performance in perfect lab conditions—we're trying to make these systems hold up in the **messiness of actual water streams**.

Threads 5 & 6: Engineered and Hybrid Materials

Hybrid Materials for Multifunctionality

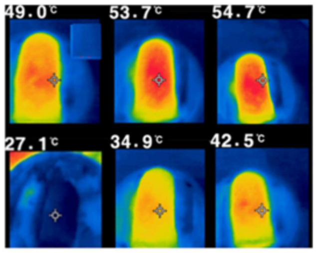


Focus: Integrating enzymes, metals, and carbon frameworks

Hybrid Systems:

- **Laccase-immobilised composites**
- **3D rGO frameworks (N-doped and Ag-doped)**
- **$CuFe_2O_4$-doped rGO solar absorbers**

- **Insight:** Hybrid systems bridge biological and advanced material functionality



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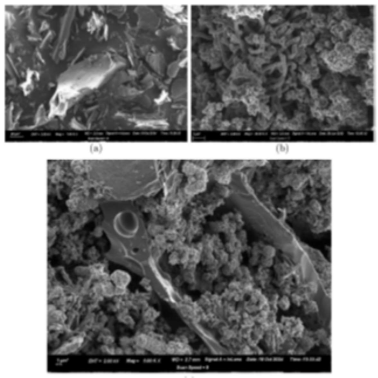
- Now, as our journey continues through the material threads, we reach one of the most exciting intersections — **hybrid materials**.
  This is where we start blending biology, chemistry, and nanotechnology — where we don't just remove pollutants, we create multifunctional systems that sense, degrade, and adapt.
- 💡 *Let's start with the laccase-immobilised systems.*
  We developed **ZnO–PANI–Laccase composites** and **chitosan-alginate beads** that immobilise enzymes for remarkable stability.
  These aren't just materials — they're like living hybrids that can **electrochemically detect and degrade pharmaceuticals**, including antibiotics and surfactants like CTAB. So now, our materials don't just adsorb — they *act*, and *respond*.
- Then, we moved to **3D reduced graphene oxide frameworks**, both **nitrogen- and silver-doped**.
  These structures harness **solar energy** — removing dyes, phenol, and antibiotics under sunlight, bridging materials science with clean energy innovation.
  In one phrase — it's *pollution cleanup powered by the sun*.
- Finally, **$CuFe_2O_4$-doped graphene solar absorbers** extended our vision further — supporting **solar desalination**, integrating water purification with renewable energy.
- ✨ And that's really the insight here:
  Hybrid systems are *beyond adsorption*. They merge **biological and material functionality** — bringing us closer to a world where materials are smart, sustainable, and circular by design."

Threads 5 & 6: Engineered and Hybrid Materials

Innovation Drivers and Sustainable Impact



Key Design Strategies:

- Metal selection (Ni, Co, Ag, $CuFe_2O_4$)
- Support matrices (PANI, rGO, biochar, PVPP, chitosan)
- Enzyme integration

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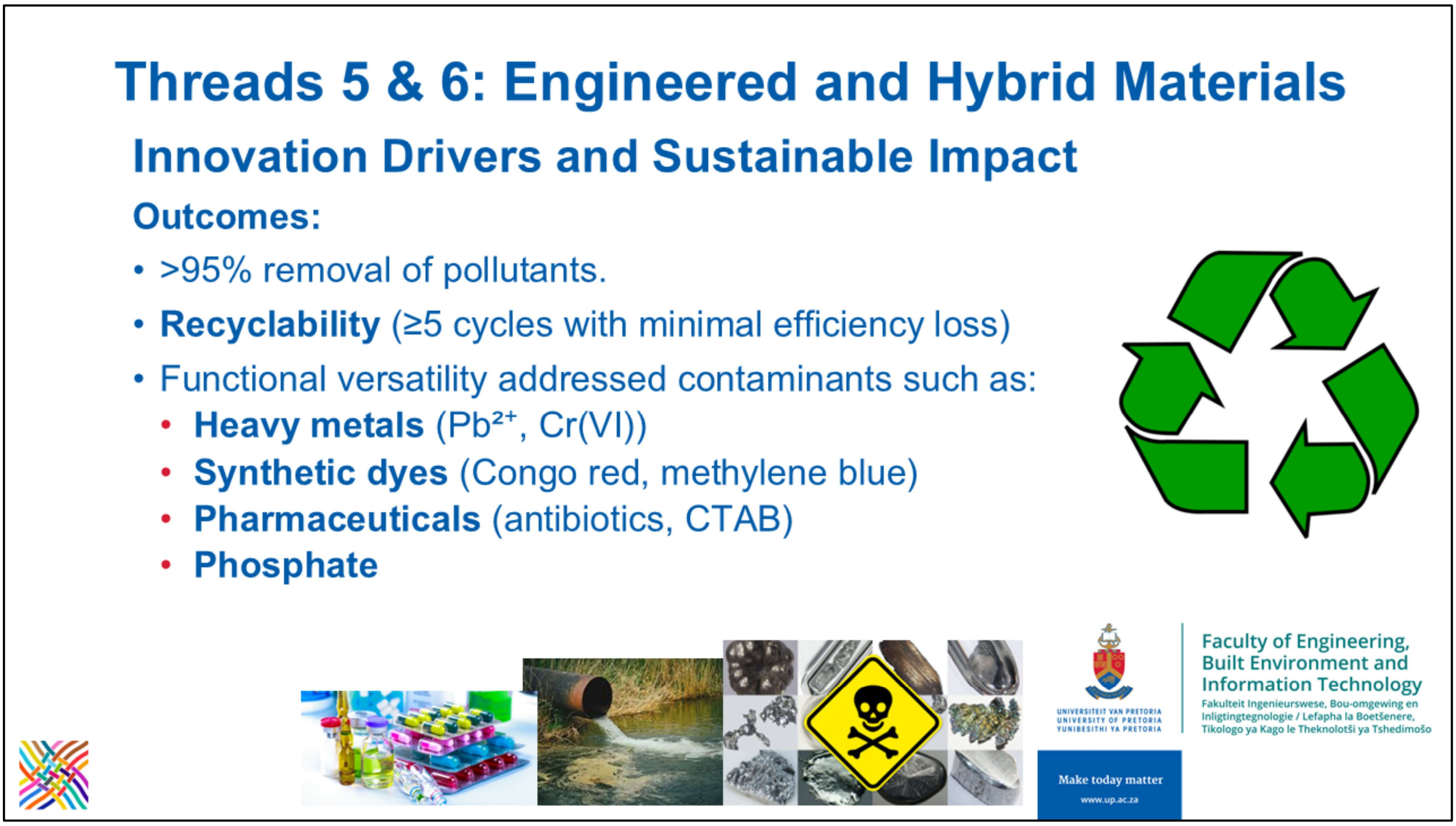
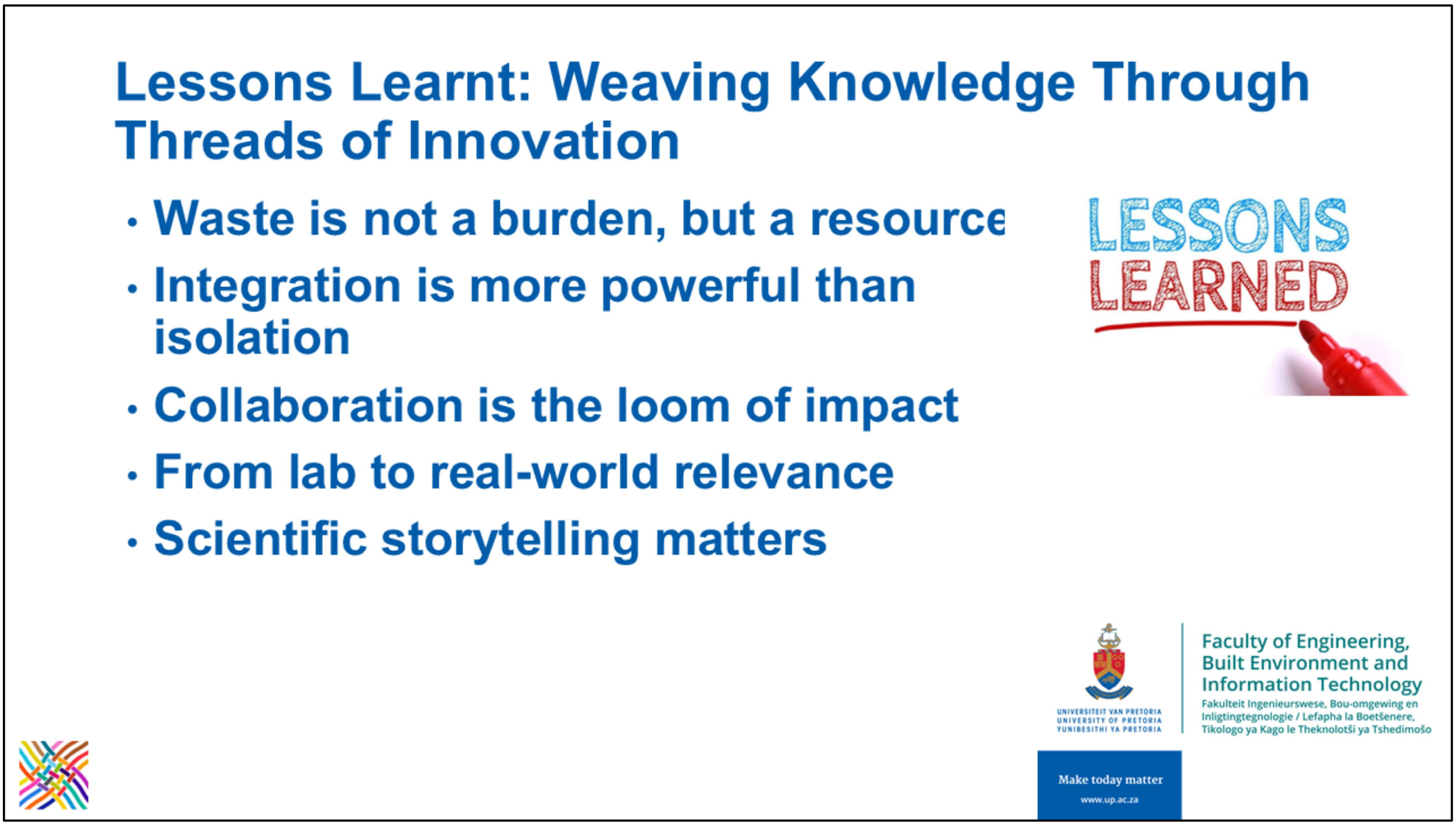
- “So now we reach the culmination of these material development threads — where chemistry, structure, and sustainability really come together.”
- “What we found was how carefully tuning both the *composition* and *architecture* of materials changes everything — from how fast pollutants are captured to whether a catalyst can be reused again and again.”
- **Metal selection matters.**
  “By choosing the right metals — nickel, cobalt, silver, even $CuFe_2O_4$ — we could control oxidation strength, electron transfer, and durability. In short: we made the materials think smarter.”
- **Support matrices give structure and soul.**
  “By embedding these metals in supports like polyaniline, reduced graphene oxide, biochar, PVPP, or chitosan, we enhanced not only stability but recyclability. The scaffolds turned reactive powders into real, reusable systems.”
- **And then there’s enzyme integration.**
  “That’s where the biological meets the engineered. Enzymes gave the systems specificity and let them work under mild, environmentally friendly conditions — something industrial chemistry still struggles with.”
- **(Pause to connect the dots)**
  “So this is the essence of the ‘engineered and hybrid materials’ thread — bridging molecular precision with sustainable design. Each innovation here is a step closer to scalable, greener, and smarter technologies for real-world water challenges.”

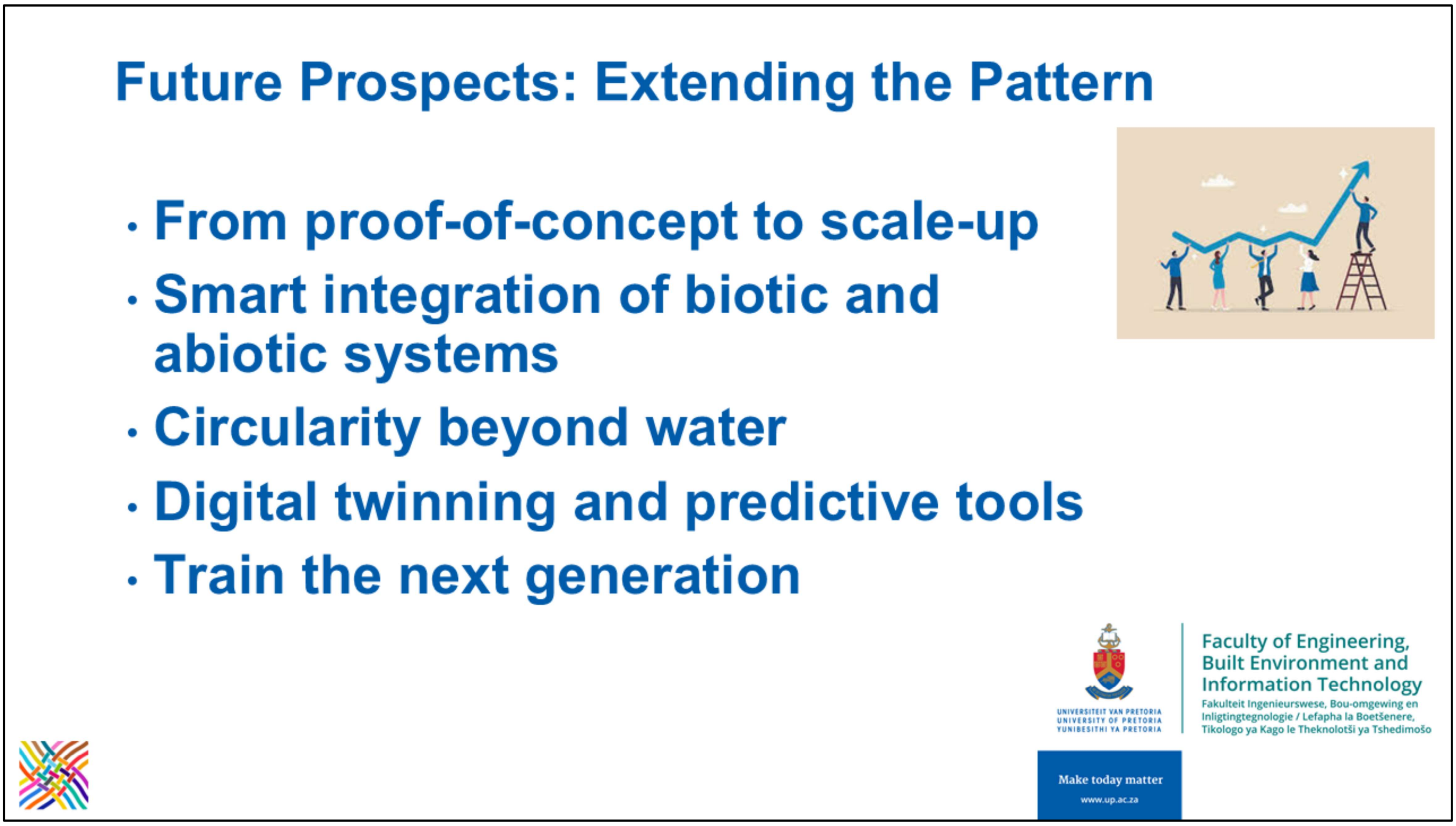


- Ultimately these materials were never designed to merely remove pollutants — they were designed to *keep performing*.
  We achieved more than 95% pollutant removal or degradation across multiple systems — whether for metals, dyes, pharmaceuticals, or phosphates. But just as important, they could be reused for at least five cycles with minimal loss in efficiency — demonstrating real potential for scalability and sustainability.
- Each of these systems shows a kind of ‘functional versatility’ —
  they target not just one pollutant, but a *suite* of them: heavy metals like lead and chromium, synthetic dyes, antibiotics, surfactants, even phosphates.
- So, while the chemistry is intricate, the message is simple:
  We can design materials that are *smart, sustainable, and circular* — materials that not only clean water but also clean up our industrial footprint.”



As I look back across all these threads — from microbes to materials, from mining residues to hybrid nanocomposites — a few lessons have really stayed with me.

- First, **waste is not a burden, but a resource**. Across every project, we've seen that value lies hidden in what society discards — whether it's bacteria, bark, or mine sludge.
- Second, **integration beats isolation**. The real breakthroughs came when we bridged disciplines — chemistry, biology, materials science, and engineering — to create something neither could achieve alone.
- Third, **collaboration is the loom of impact**. Every success story was woven by students, postdocs, colleagues, and international partners. It's the collective effort that gives the research both structure and strength.
- Another key point — **relevance matters**. Translating lab results into real-world, scalable systems — like AMD-derived adsorbents or enzyme composites — has been essential in proving sustainability beyond theory.
- And finally, I've realised the power of **storytelling in science**. The metaphors — threads, weaving, loops — weren't just visuals. They've helped communicate complexity in a way people connect with — even inspiring tools like the *P-Game* for policy engagement.
- Ultimately, these lessons remind me that science doesn't just solve problems — it creates connections."



- As we look ahead, the question becomes: *How do we take what we've built — these six threads — and weave them into something even stronger?*
- 🔬 **From proof-of-concept to scale-up:**
  - Many of these technologies — from our PANI-based composites to immobilised fungi and AMD-derived adsorbents — have proven themselves in the lab. The next step is to move into pilot and industrial applications, where real impact happens.
- 🌞 **Smart integration of biotic and abiotic systems:**
  - We're already seeing how enzymes, biofilms, and solar-driven materials can work together. The future lies in hybrid systems — bringing biology and chemistry into harmony for water purification and green production.
- ♻️ **Circularity beyond water:**
  - Waste valorisation shouldn't stop at water. The same principles can guide soil remediation, air purification, and even catalyst regeneration — truly closing the loop in multiple sectors.
- 💻 **Digital twinning and predictive tools:**
  - With AI, modelling, and biosensors, we can now *see* and *control* these processes in real time — merging mechanistic insight with machine learning to optimise both the science and sustainability.
- 🎓 **Training the next generation:**
  - And finally, none of this endures without people. The next step is building transdisciplinary researchers — engineers who think like ecologists, and scientists who understand policy.

- I'd like to close by recognising the people who have made this journey possible.
- First and foremost, my wife **Kim**, and my daughters **Ella** and **Audrey** — your patience, love, and laughter are my anchor. Kim, you've been the cornerstone of everything I've done; life would be far duller without my girls keeping me on my toes.
- To my **parents**, thank you for instilling in me a deep respect for hard work, curiosity, and kindness — values that have guided me throughout this journey. And to my **siblings**, thank you for your support, humour, and the grounding that only family can provide.
- My PhD supervisor, **Prof. William Nicol** — you saw potential long before I did, and your continued belief shaped much of the academic that I've become.
- **Prof. Evans Chirwa**, my steadfast mentor and ally — your support and friendship have made the last decade not only productive but deeply rewarding.
- **My collaborators** — specifically Prof. Arjun Maity, Dr. Madhumitha Bhaumik, Prof. Shepherd Tichapondwa, and Dr. Nils Haneklaus — who have become more than colleagues; they are dear friends. Your creativity, rigour, and kindness have made the journey richer and more rewarding throughout.
- To my **colleagues in the Department of Chemical Engineering**, thank you for your constant encouragement and camaraderie — I'm proud to be part of such an exceptional team.
- And finally, to my **students and postdocs** — you are the true weavers of innovation. Without your creativity, persistence, and insight, none of these projects would have taken shape. You gave colour and life to every idea we pursued.