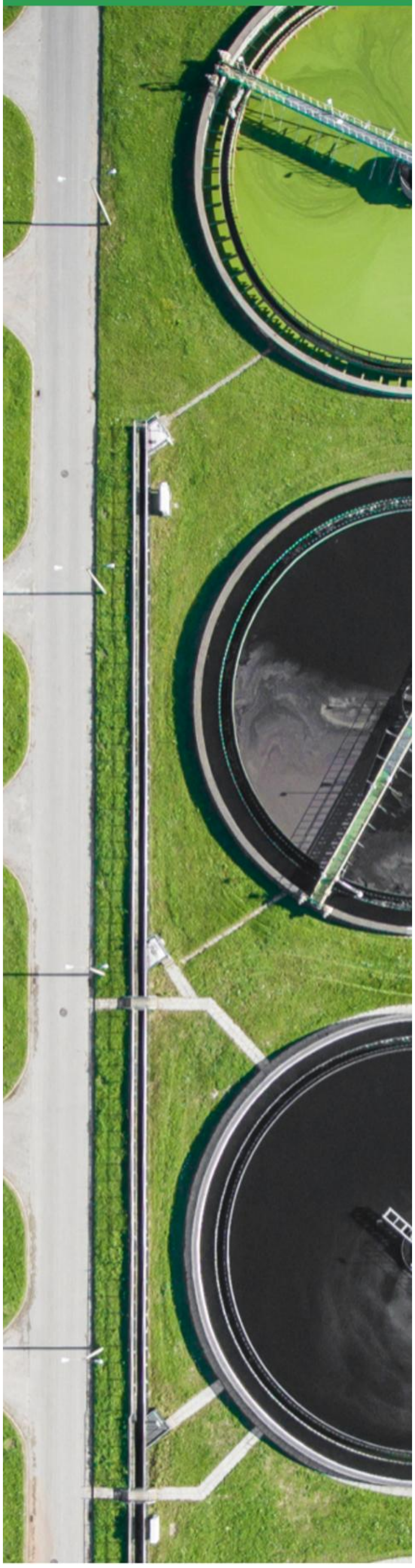

Future Directions of Biosolids

Developing non-agricultural applications for biosolids transformed products (Project 2C)

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A report of Project 2C of the ARC Training Centre for the Transformation of Australia's Biosolids Resource

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About the Centre
The ARC Training Centre for the Transformation of Australia's Biosolids Resource has a primary goal of delivering world-class and innovative technological solutions and knowledge in biosolids transformation, to train the next generation of biosolids practitioners in cutting-edge, transformational approaches, and to guide best practice in the biosolids sector.

About the Project
A key project delivered by the Centre is Future Direction of Biosolids (Project 2C), which seeks to explore plan B option for biosolids management due to the current uncertainties in the traditional land application option as a result of increasing concern with contaminants and emerging stringent regulations. The aim is to demonstrate the range of opportunities with transformed products from the thermal treatment of biosolids, focusing on the non-agricultural applications of biosolids derived biochar and hydrochar products to create a circular solution within and outside the water.

For further information visit: www.transformingbiosolids.com.au

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Executive summary

This report is part of a broader initiative under the ARC Training Centre for the Transformation of Australia's Biosolids Resource. Project 2C (Future Directions of Biosolids) aims to advance sustainable management of biosolids by exploring and validating innovative non-agricultural applications of thermochemically transformed biosolids products, particularly biochar and hydrochar. A comprehensive study to identify the potential non-agricultural application of biochar and hydrochar is impretive part of this project.

The report presents key insights and outcomes from the project **"Future Directions of Biosolids: Developing Non-Agricultural Applications for Biosolids Transformed Products".** The project addresses existing knowledge gaps in biosoilds biochar and hydorchar applications in varios areas including adsorbents, catalysts, construction, energy storage, nutrient recovery etc. The project responds to growing regulatory, environmental, and societal concerns associated with traditional land application of biosolids, especially due to the presence of persistent contaminants such as PFAS, microplastics, and pharmaceuticals. It evaluates the potential of biosolids-derived char materials generated through pyrolysis, gasification, and hydrothermal processes as viable alternatives to conventional materials in several industrial applications, thereby contributing to a circular economy.

The report identifies elevated heavy metal content in the chars as a key challenge which may limit agricultural reuse but present valuable advantages for industrial applications (e.g., catalysis, adsorption, and electrochemical devices).

A decision-making framework using the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method was established to rank and prioritize potential industrial applications of biosolids biochar based on market size, environmental benefits, technical feasibility, and readiness level. Biosoild biochar also showed excellent performance as catalysts for biogas decomposition for hydrogen production. Further modification in biochar and hydrochar structure resulted in to good electrode material and H_2S adsorbent. This project lays a foundation for redefining the role of biosolids in a resource recovery framework, advocating for industrial valorisation pathways that reduce environmental impact, improve product safety, and diversify end-use markets beyond agriculture.

Introduction

The management of biosolids, a byproduct of wastewater treatment processes, presents significant environmental and public health challenges. Traditionally, biosolids have been applied to agricultural lands due to their nutrient-rich composition. However, concerns have escalated over the presence of persistent contaminants such as per- and polyfluoroalkyl substances (PFAS), microplastics, and pharmaceuticals within these materials [1]. These contaminants pose risks of soil and water pollution, bioaccumulation in the food chain, and potential human health hazards, thereby limiting the feasibility of land application and prompting the need for alternative management strategies [2].

Thermochemical conversion processes, notably pyrolysis, have emerged as promising technologies to address these challenges. Through pyrolysis, biosolids can be transformed into biochar—a carbon-rich, porous material with potential applications in various industrial sectors [3]. This conversion not only reduces the volume of waste but also immobilizes or degrades harmful contaminants, thus mitigating environmental risks. There remains a substantial gap in exploring and validating non-agricultural applications of this material [4]. By expanding the scope of biochar applications beyond agriculture, this research endeavors to enhance the sustainability and economic viability of biosolids management, contributing to a circular economy and reducing the environmental footprint of wastewater treatment processes.

This project report investigates the application of biosolids biochar and hydrochar for nutrient recovery, catalyst for biogas cracking, PFAS removal from wastewater, additive in anaerobic digestion, supercapacitor electrodes, H_2S adsorption from biogas, potential as construction material, rubber compounding, and catalyst for chemical production. The study was guided by six core research objectives aimed at addressing critical knowledge and implementation gaps.

Pyrolysis and hydrothermal technologies, particularly pyrolysis and hydrothermal process offer promising pathways for the valorisation of biosolids by thermochemically converting them into value-added products such as biochar, hydrochar, bio-oil, and syngas [5]. These processes are particularly advantageous as they can effectively reduce waste volume and stabilize contaminants under controlled thermal conditions. Importantly, both pyrolysis and hydrothermal treatments contribute to the reduction persistent pollutants such as PFAS, microplastics, and pharmaceutical residues, improving the environmental safety profile of the resulting products. Apart from the potential to effectively reduce volume and destroy contaminants of emerging concern, the char produced from the thermal treatment of biosolids can retain nutrient value and have porous and stable carbon structure, making it a potential option for soil amendment [6]. Whilst the char produced from biosolids through thermal treatment has many benefits, it also has certain drawbacks. For instance, the thermal process typically increases the concentration of heavy metals, such as As, Cd, Cu, Hg, Cr, Ni, Pb, and Zn in the char product, which can exceeds the acceptable limits for direct application to agricultural land [7]. Also, biosolids biochar can be contaminated with polycyclic aromatic hydrocarbons and other residual persistent organic contaminants that can be toxic to human health. The major limitations around heavy metals contamination is largely for land applications, and it might be a strength outside this sector.

Therefore, non-agricultural uses of char derived from biosolids can increase its value without potential transfer of contaminants to the environment. The potential for non-agricultural applications of the biochar span across adsorption, catalysis, energy storage, additives in construction and rubber compounding, nutrient recovery, and substitution for coal. Figure 1 depicts a circular economy concept in wastewater treatmt plants for transforming biosolids into biochar. This report presents the outcomes of a comprehensive study undertaken as part of the ARC Training Centre for the Transformation of Australia's Biosolids Resource, focusing on the development of non-agricultural applications for biosolids-derived biochar and hydrochar. The research explored the physicochemical characteristics of thermochemically transformed biosolids—via pyrolysis, hydrothermal process and evaluated their suitability for various industrial applications. Special emphasis was placed on understanding the fate and transformation of contaminants such as heavy metals, PFAS, and microplastics, and on identifying strategies (e.g., acid-alkali modification, co-treatment) to enhance product performance while minimizing environmental risks.

A core aspect of the project was the experimental validation of biosolids biochar in non-agricultural domains, including nutrient recovery, PFAS removal, H_2S adsorption, catalysis for biogas cracking, supercapacitor electrode materials, and rubber compounding. A decision-support tool using the TOPSIS method was also developed to systematically prioritize applications based on technical feasibility, market potential, and environmental impact.

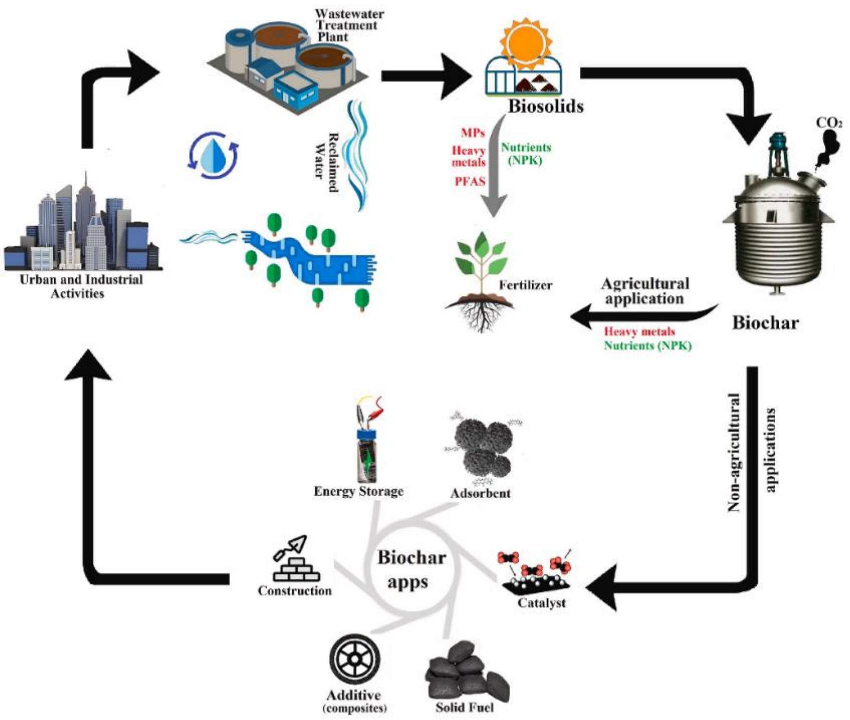

Figure 1: The potential non-agricultural routes for utilizing biochar derived from biosolids within a circular economy framework.

This work represents a transformative approach to biosolids management by shifting the focus from land application to industrial valorization pathways, aligning with national goals around waste minimization, circular economy, carbon footprint reduction, and sustainable infrastructure. It paves the way for scalable deployment of biosolids-derived materials in high-value sectors, promoting both environmental resilience and economic viability.

Purpose of this project

The primary aim of this project is to explore and advance the non-agricultural applications of biosolids-derived biochar and hydrochar produced through thermochemical processes such as pyrolysis and hydrothermal process. The focus is on understanding the physicochemical properties of these transformed products, identifying performance-enhancing treatment strategies, and evaluating their functionality across a range of industrial applications. This research addresses critical knowledge gaps in the valorisation of biosolids beyond traditional land applications and aims to enable scalable, environmentally safe, and economically viable pathways for product use in diverse sectors.

The project is structured around the following specific research objectives:

- Objective 1: Investigate and compare the physicochemical properties of biochar and hydrochar derived from biosolids under varying thermal and hydrothermal conditions.
- Objective 2: Assess the effectiveness of biochar and hydrochar modification strategies, including acid-alkali treatment in enhancing adsorption capacity, catalytic activity, and contaminant immobilization for targeted applications such as nutrient recovery, PFAS removal, and H_2S adsorption.
- Objective 3: Evaluate the suitability of biosolids-derived biochar as a catalyst in energy systems (e.g., biogas cracking for hydrogen and carbon nanomaterials) and as an additive in anaerobic digestion processes to enhance methane production and reduce ammonia toxicity.
- Objective 4: Investigate high-value, non-agricultural applications including use in supercapacitor electrodes, construction materials (e.g., cementitious composites), and rubber compounding as a partial substitute for carbon black.
- Objective 5: Contaminant mapping to assess the fate and transformation of persistent pollutants (e.g., heavy metals, PFAS, microplastics) during thermal and hydrothermal processing.
- Objective 6: A preliminary techno-economic assessment to evaluate the commercial viability and scalability of selected applications.

Our approach

This project adopts a systematic and multidisciplinary research framework to investigate and validate non-agricultural applications of biosolids-derived biochar and hydrochar, with the overarching objective of transitioning biosolids management from conventional disposal practices toward value-added resource recovery pathways.

The approach integrates the following six key components:

1. **Literature Review and Application Mapping**

   A comprehensive review of existing scientific literature and industry practices was conducted to identify the broad spectrum of potential non-agricultural applications for biosolids-derived char materials. This helped frame the scope of the research and highlight high-potential application areas requiring further investigation.

2. **Development of a Decision-Support Tool**

   A **TOPSIS (**Technique for Order of Preference by Similarity to Ideal Solution) based ranking model was developed to evaluate and shortlist promising applications based on factors such as technical performance, market size, environmental benefit, economic viability, and regulatory alignment. This tool supports transparent and strategic decision-making for future research and investment.

3. **Experimental Validation**

   Laboratory-scale experiments were undertaken to evaluate the suitability of biosolids biochar in several priority applications:

   - **Nutrient recovery** from wastewater using modified biosolids biochar.
   - **Catalytic use** of biochar in biogas pyrolysis for hydrogen and carbon nanomaterials production.
   - **H_2S adsorption** from biogas streams using chemically treated char products.
   - **PFAS adsorption** from trade wastewater
   - **Active electrode materials** in supercapacitors
   - **Rubber Compounding**
   - **Additives** in anaerobic digestion systems
   - **Catalysts for biomass bio-oil cracking** for phenolics production
   - **Construction applications (Literature Review)**

4. **Product Improvement through Pre-treatment and Modification**

   Acid-alkali treatments were applied to enhance the surface properties and adsorption capacity of biosolids biochar. These modifications aimed to increase the material's effectiveness and applicability in advanced industrial systems.

5. **Contaminant Mapping and Risk Assessment**

   Detailed analysis was conducted to track the fate of **PFAS, heavy metals, microplastics, and other persistent contaminants** during thermal and hydrothermal processing. This component ensures the safe use of biosolids-derived products by identifying and mitigating environmental, reputational and health risks.

6. **Techno-Economic Assessment and Industry Engagement**

   Preliminary techno-economic analysis (TEA) was performed to estimate the financial feasibility and market potential of selected applications.

Key Research findings

This project successfully addressed several critical knowledge gaps related to the non-agricultural applications of biosolids-derived biochar and hydrochar, focusing on their production, modification, and functional performance across a range of industrial uses. The key findings are summarized below, organized according to the major applications.

Shortlisting: Developing a decision-making tool

This approach allowed for the integration of both qualitative and quantitative parameters—including market size, application readiness, environmental benefit, preparation complexity, and economic value—into a unified evaluation framework. Applications such as catalysts for biogas cracking, electrochemical materials for supercapacitors, H_2S and PFAS adsorption, and nutrient recovery scored highly based on their proximity to ideal performance, scalability, and market relevance. The TOPSIS analysis proved instrumental in narrowing down the broad landscape of potential uses and guided the selection of applications for experimental validation and techno-economic assessment (Table 1).

Table 1: TOPSIS Analysis

Shortlisting Non-agricultural Applications using TOPSIS Method							
	Beneficial	Beneficial	Non Benf.	Non Benf.	Non Benf.	Beneficial	Non Benf.
weightage	0.25	0.05	0.2	0.05	0.1	0.2	0.15
	Comparative Performance	**Market Size**	**Distance to application**	**Pre-treatment**	**Preparation Cost**	**Market Price**	**Environment /emission**
Liquid Adsorption	0.5	20000000	50	3	400	1500	5
Gas Adsorption	0.5	5000000	1	3	400	1500	5
Nutrient Recovery	0.3	1E+09	1	3	400	1500	1
Catalyst (CVD)	0.7	5000000	50	3	500	3000	7
Additive (AD)	0.3	100000000	1	3	400	500	6
Catalyst (Fenton)	0.2	10000000	1	2	300	600	3
Rubber Compounding	0.5	5E+09	100	1	150	1500	1
Construction	0.5	4E+09	100	1	150	250	1
Ink Production	0.25	100000000	300	4	600	1700	5
Electrochemical	0.8	100000000	50	3	400	2000	7
Zeolite Production	0.5	60000000	100	4	800	500	5
Solid Fuel	0.2	7E+10	100	1	50	100	10

* Data in the table are from literature or assumed.

Nutrient Recovery

- Biosolids biochar, particularly after mild acid-alkali treatment, showed significantly enhanced ammonium (NH_4^+) adsorption capacity—from <2 mg/g (raw) to ~17 mg/g (treated).
- Performance from real digester effluent was comparable to that of commercial ion-exchange resins, making it a viable substitute.
- The treated biochar met regulatory thresholds for most heavy metals and qualified as C1 or Grade A biosolids, supporting its safe reuse.

Catalyst for Biogas Cracking (Hydrogen & CNM Production)

- Biosolids-derived biochar demonstrated strong catalytic performance for methane decomposition, with CH_4 conversion efficiencies of 90–95% and CO_2 conversion of 85–90%.
- Compared favourably with commercial catalysts such as NiMo/MgO and CoMo/MgO.
- This application offers a pathway for hydrogen production and carbon nanomaterial (CNM) synthesis from biogas, contributing to clean energy initiatives.

H_2S Adsorption from Biogas

- Alkali-activated biochar exhibited H_2S removal capacities up to 67 mg/g, far exceeding that of raw biochar (~4.5 mg/g).
- Acid-treated hydrochar and biochar also demonstrated substantial improvement, confirming that surface modification significantly enhances adsorption performance (Fig 2).

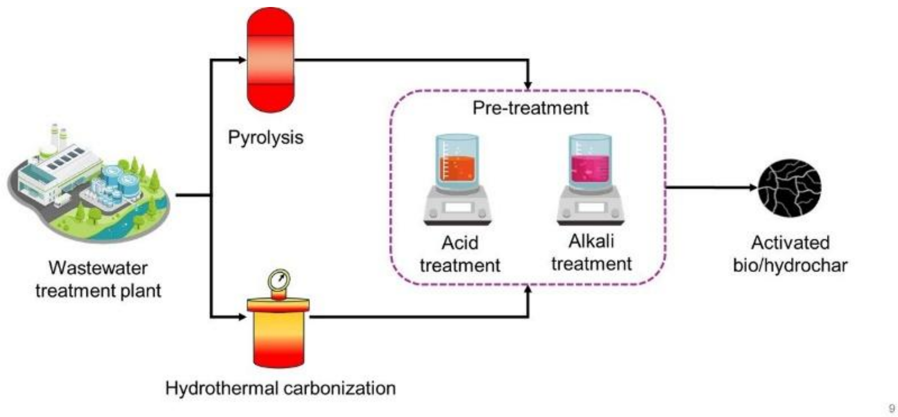

Figure 2: Approach for H_2S adsorption

PFAS Removal from Trade Wastewater

- Unmodified biosolids biochar removed PFOS, PFOA, and PFHxS with ~65–88% efficiency.
- Surface-modified CNM-coated biochar improved removal to >97%, approaching the effectiveness of granular activated carbon (GAC).

Biochar as additives in AD systems

- Biochar (BC) and Treated Biochar (TBC) resulted in a significant reduction of 8 days in the lag phase. On day 18, BC and TBC digesters produced biomethane which is 58.2% and 88.5%, respectively higher than the control.
- The total ammonia nitrogen concentration was reduced in the digesters with BC and TBC by 25% and 35.5%, respectively.

Electrochemical Applications (Supercapacitors)

- Modified biosolids biochars achieved specific capacitances up to 30.33 F/g, energy densities of 4.21 Wh/kg, and power densities of >2000 W/kg.
- While performance still lags behind advanced materials like graphene, KOH activation and CNM coating markedly improved electrochemical properties.
- This work opens new avenues for using biosolids in energy storage technologies, though further optimisation is required.

Rubber Compounding

- Biosolids biochar (especially at 600 °C) exhibited physical and chemical characteristics comparable to commercial carbon black.
- Could replace up to 50% of carbon black in rubber formulations, offering cost and environmental benefits.

Catalysts for biomass bio-oil cracking for phenolics production

- A high content of phenolics (69.7 area%) and hydrocarbons (13.7 area%) was observed in the bio-oil product with H_3PO_4-activated biosolid carbo-catalyst (PAC) compared to KOH-activated (KAC) and non-activated carbo-catalyst (BC) at optimized pyrolysis temperature, i.e., 400 °C.

Construction Materials

- Biosolids biochar showed high levels of CaO, SiO_2, and Fe_2O_3, indicating cementitious potential.
- Material properties aligned with requirements for cement and concrete additives, particularly in plaster and asphalt.
- Although not yet experimentally validated at scale, the findings support systematic investigation into mechanical strength and durability for civil applications.

Contaminant Mapping

- Mapping results were visualised across various stages (raw sludge → treated biosolids → char products), establishing a comprehensive risk profile for each end-use.
- These insights are critical for ensuring that non-agricultural applications remain environmentally safe and comply with relevant regulatory thresholds.

Techno-Economic Analysis (TEA)

- Findings suggest that economic feasibility is highly application-dependent, with value-added products like adsorbents, catalysts, and composite materials showing the most promise for cost recovery and potential revenue generation.
- TEA outcomes also identified uncertainties and sensitivities (Fig 3), reinforcing the importance of pilot-scale validation and targeted market development to improve investment confidence.

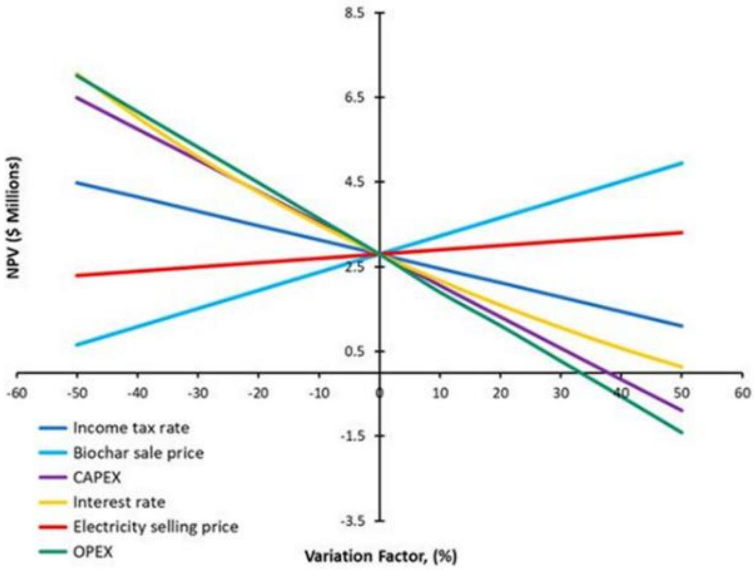

Fig 3: Techno-economics scenario analysis

Contributions and Impact

While traditional biosolids use has focused predominantly on land application, this project shifts the paradigm toward high-value industrial applications. .

- It expands the scope of biochar use by validating their applicability in advanced sectors such as nutrient recovery, biogas purification (H_2S removal), hydrogen production, PFAS removal, supercapacitor electrodes, construction materials, and rubber compounding.
- Preliminary techno-economic assessment provided critical understanding of the commercial feasibility of proposed applications, laying the groundwork for industry engagement and future scale-up.

The findings provide valuable input for the development of future regulatory frameworks, standardisation guidelines, and technology transfer initiatives.

Future Recommendations

This project 2C has sparked several new insights, creating opportunities for further exploration. To expand on the current findings, the following recommendations are proposed for future research.

- Undertake life cycle assessments to quantify the environmental benefits and trade-offs associated with mentioned biochar applications..
- Engage stakeholders from relevant sectors for adoption of biosolids-derived char materials.

Achievements

Publications:

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