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Session

The 4th Symposium on Innovation and Sustainability
"Biomass and Biochar Utilization in the ASEAN Context"

International Development and Prospects of AI Applications in Biomass and Biochar Utilization

Current Status, Commercialization Challenges, and Improvement Strategies

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12 November 2026
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Keng-Tung Wu, PhD

International Development and Prospects of AI Applications in Biomass and Biochar Utilization

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OUTLINE

0. NCHU Bioenergy Research Core Lab
1. AI is Coming
2. Why Biochar x AI Is Emerging Now
3. International Research Landscape
4. Applications of AI on Biochar Research
5. Current Challenges
6. Future Actions

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International Development and Prospects of AI Applications in Biomass and Biochar Utilization

0. NCHU Bioenergy Research Core Lab

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PhD in Chemical Engineering, University College London (UCL), UK (1997)

Associate Professor, Department of Forestry
Associate Professor, Master Program of Agricultural Economics and Marketing
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National Chung Hsing University (NCHU), TAIWAN

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Engaged in gasification research for 27 years
biochar research for 15 years

Research Interests

- Biomass Thermochemical Conversion (gasification, pyrolysis, torrefaction, etc.)
- Fluidisation Engineering
- Bioenergy Integrated with Microgrids
- Biochar Production & Application
- CO_2 Technology
- Chaotic Dynamics
- APEC Energy Policy



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Where We are?



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NCHU since 1919

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Bioenergy Research Core Laboratory

National Chung Hsing University, TAIWAN



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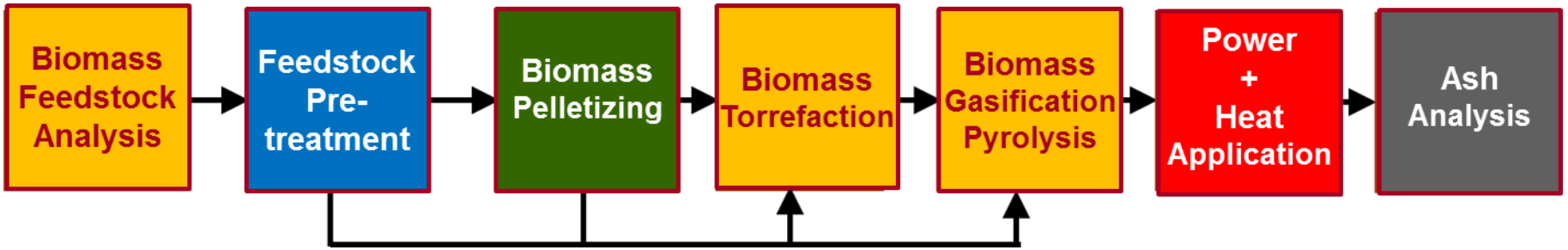
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NCHU Bioenergy Research Core Laboratory (2007)

Educational Laboratory of Ambient Experience for Bioenergy (2011)



Fully Biomass Thermochemical Process Practice Lab

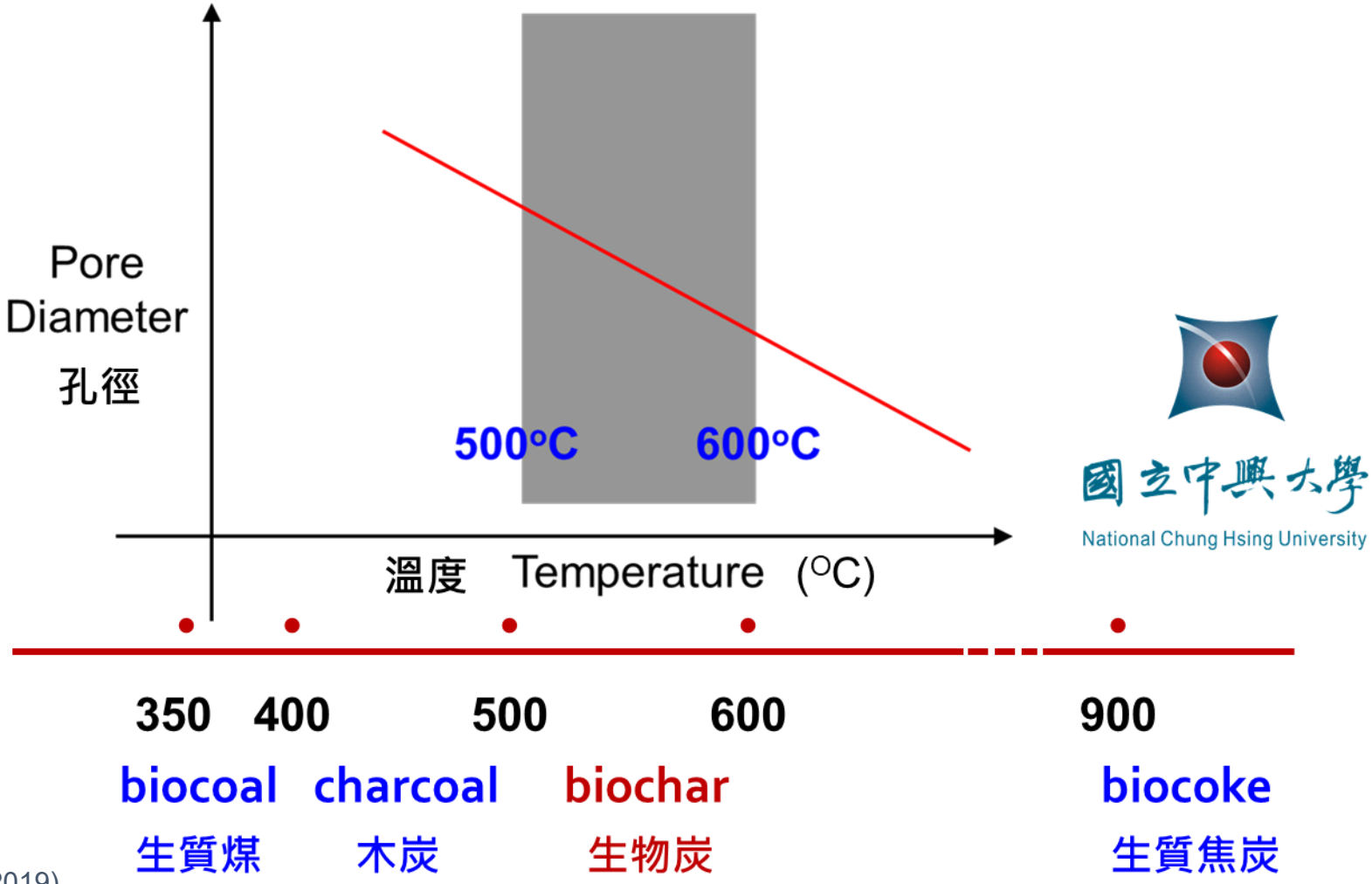
The First and Only One in Taiwan

教育部大專能源科技人才培育資源中心計畫
生質能科技人才培育資源中心
【生質能情境體驗教室】特色實驗室
Resource Center for Talent Training in Biomass Energy Technology
Educational Laboratory of Ambient Experience for Bioenergy



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My Mechanism on Biochar Research: Pore of Biochar



Source: Wu (2019)

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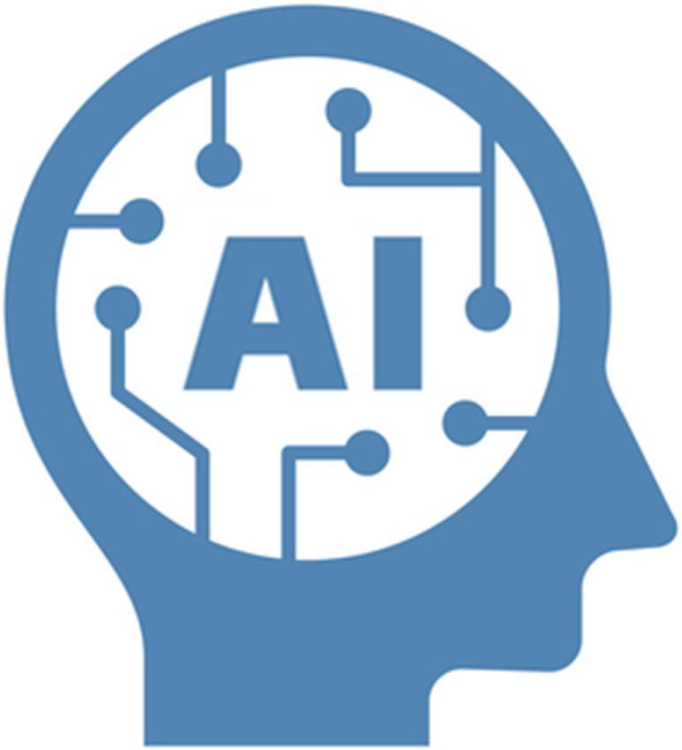
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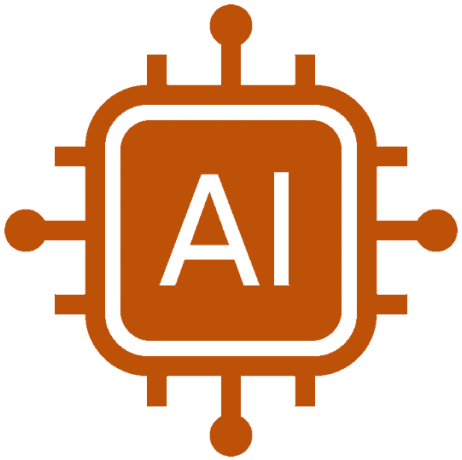
1. AI is Coming



AI Experience

Have You Used AI Today?



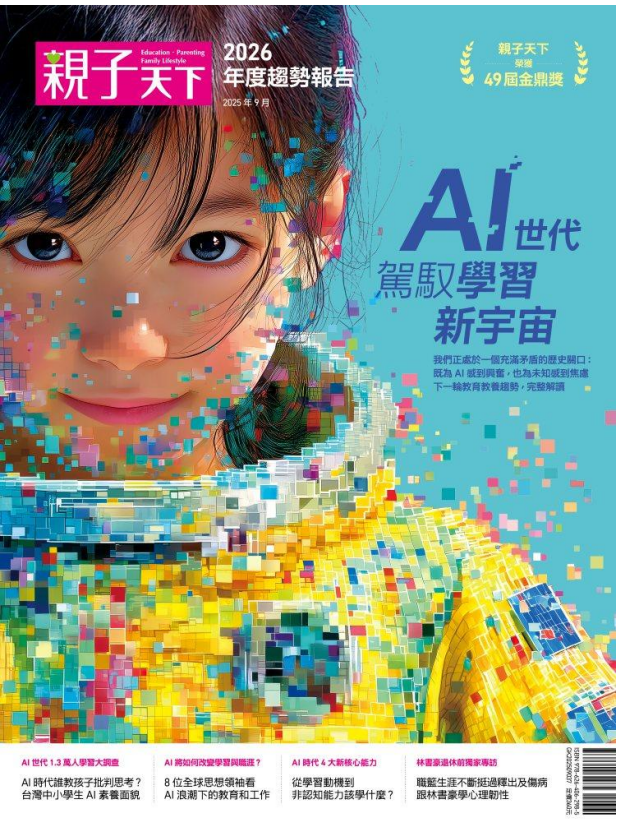


AI : Artificial Intelligence

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Survey of AI Literacy among K12 Taiwanese Students (Grade 5 to 9)



Source: CommonWealth Parenting (2025)



Students all have an AI Swiss Army knife, but use it only as a translation tool.

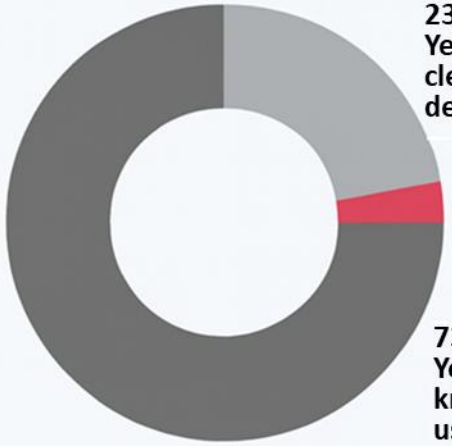
Q: Have you heard of AI?

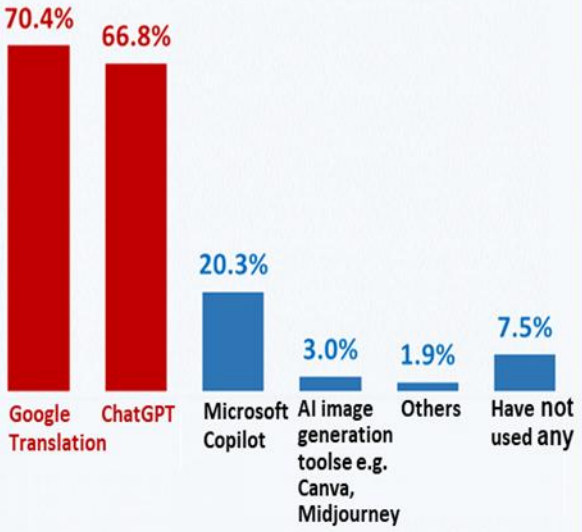
Only 3% of elementary and junior high school students have never heard of AI.

Q: Which AI tools have you used?

Multiple selections allowed, up to 2 choices.

70% have used Google Translate and ChatGPT.





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Source: Hemdale Film Corporation (1984)

The Terminator (1984)

In 2029, the AI machine "SkyNet" is trying to eliminate all remaining human survivors……

- **Question**

After all humans have been eliminated,
what will the robots do?

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AI Experience: Cooking

Today	Tomorrow	Future
		

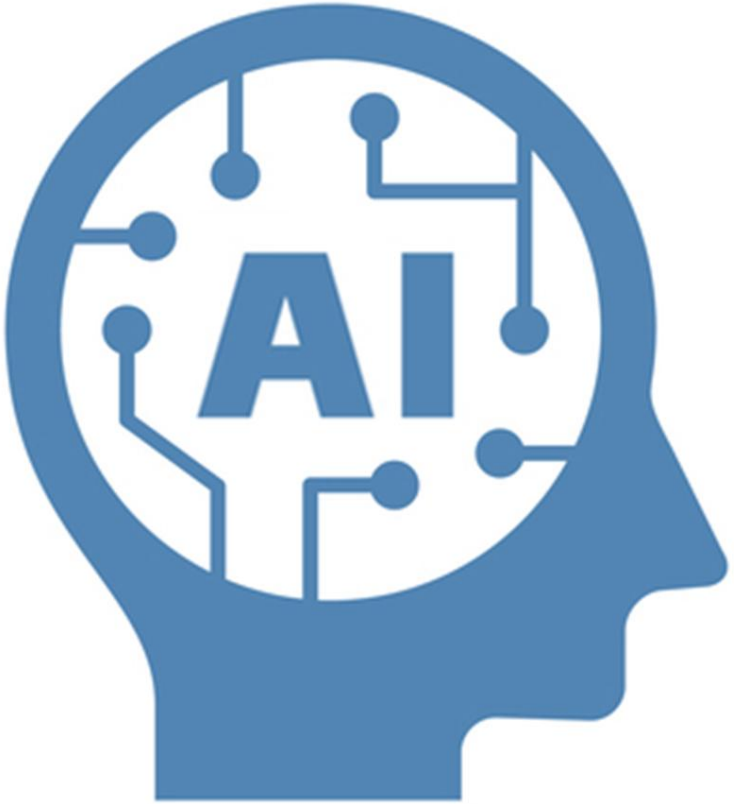
You're still the one who eats: Humans.

Source: annaolson.ca; www.sohu.com; TV Tokyo

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AI Experience:



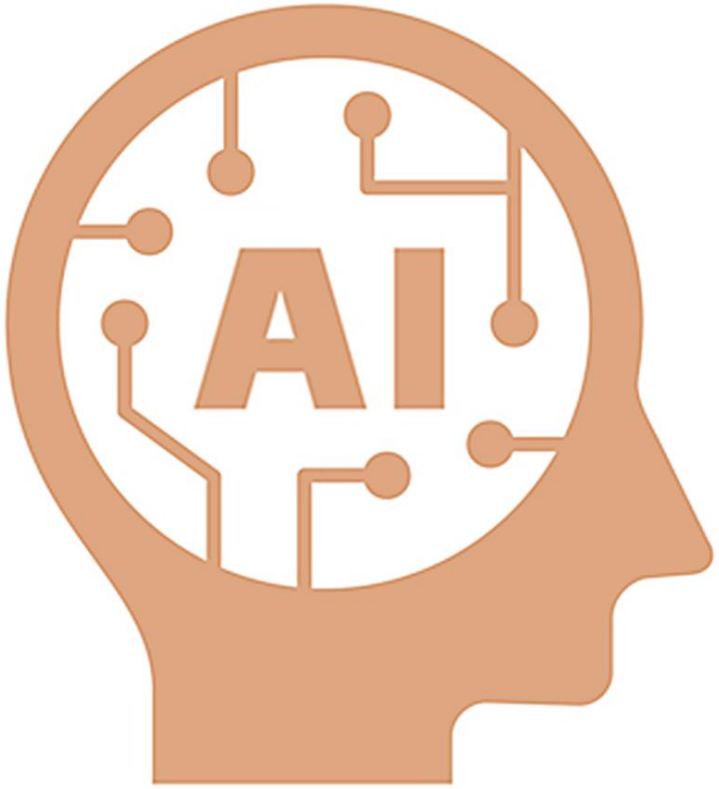
AI

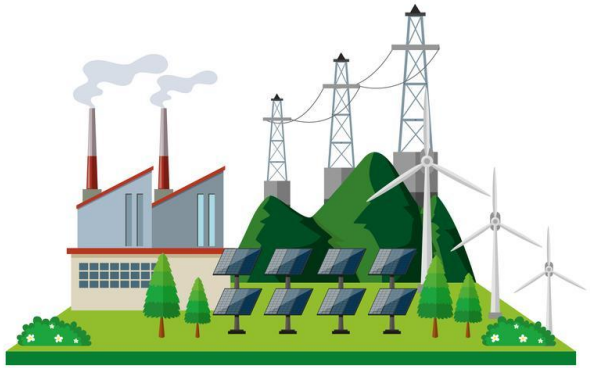
AI is your work partner,
not your subordinate.

AI is your co-pilot,
not your driver.

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The Two Key Elements of AI ?







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Core AI Technologies

Machine Learning (ML)	Trains models with data to automatically identify patterns and make predictions.
Deep Learning (DL)	Based on artificial neural networks; supports image recognition, speech recognition, natural language processing, and related technologies.
Natural Language Processing (NLP)	Used for voice assistants, intelligent customer service, document summarization, translation, and more.
Computer Vision	Applied in industrial inspection, medical imaging, smart transportation, and other fields.
Generative AI	Examples include ChatGPT and DALL·E; capable of generating text, images, music, code, and other content.
Reinforcement Learning	Widely used in game AI, robot control, and autonomous driving.

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2. Why Biochar x AI Is Emerging Now

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Bioenergy Enters the Data-Driven Era



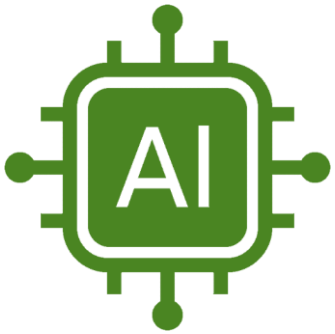
- AI
- Machine Learning
- Digital Twins

- AI and machine learning are advancing in bioenergy and the bioeconomy.
- Machine learning and advanced optimization tools are being applied to biomass conversion processes.
- AI supports process optimization, scale-up, and system control.
- Machine learning helps improve material design and performance prediction.
- Digital twins enable data-driven monitoring, simulation, and decision-making.
- Bioenergy is moving toward a smarter, data-driven development model.

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Introduction

- AI does not replace biochar experiments; it makes them more targeted, interpretable, and scalable.
- Machine learning is becoming a decision-support layer for biochar production, environmental applications, and carbon removal assessment.



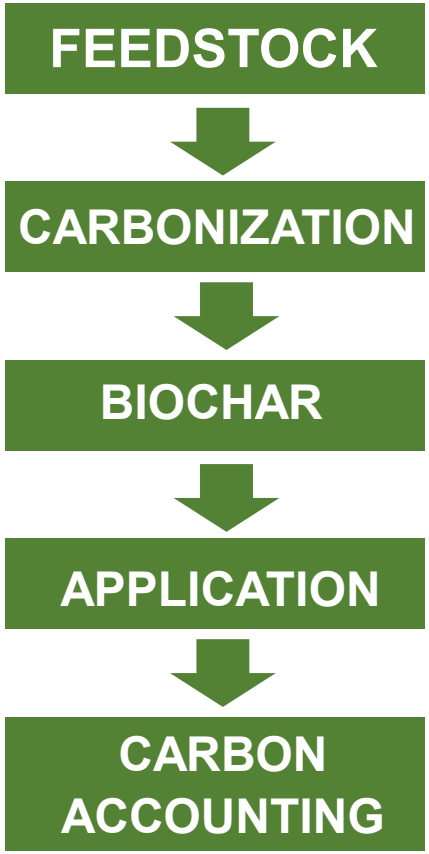


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Introduction

■ AI provides the predictive layer across the whole chain.

- Biochar research involves heterogeneous feedstocks, nonlinear thermal conversion, and application-specific outcomes.
- AI / ML helps connect feedstock characteristics, process parameters, material properties, and environmental performance.
- Current international work is strongest in property prediction, adsorption modeling, and process optimization.
- The next frontier is AI-assisted carbon sequestration assessment, precision soil application, and digital MRV (Monitoring, Reporting and Verification).



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Why Biochar x AI Is Emerging Now

➢ **The research field has reached a point where data-driven tools can reduce trial-and-error.**

1	2	3
More data	**More complexity**	**More climate pressure**
Biochar studies increasingly report feedstock, process, characterization, and performance data.	Biochar function depends on interacting variables that are difficult to capture with simple linear models.	Carbon neutrality, carbon removal, and agricultural GHG mitigation require credible decision support.

- Higher-value biochar requires matching feedstock, thermal process, and application context.
- AI can help prioritize experiments before costly pilot- or field-scale testing.

Ref: Wang et al. (2024); Li et al. (2025)

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3. International Research Landscape

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Biochar x AI Studies Cluster around Five Main Application Areas

Production	Yield, fixed carbon, surface area, activation conditions
Adsorption	Water pollutants, nutrients, dyes, heavy metals, ammonia nitrogen
Soil & Crops	Crop yield, soil organic carbon, N_2O emissions, fertilizer response
Carbon Sequestration	Stability, CO_2 adsorption, long-term storage potential
MRV & LCA	Carbon accounting, life-cycle assessment, digital verification

- International trend: moving from single-purpose prediction toward **integrated** biochar design and climate decision support.

Ref: Wang et al. (2024); Li et al. (2025)

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AI Methods Used in Biochar Research

- **Different AI methods serve different parts of the biochar research cycle.**

Random Forest / XGBoost	Robust prediction and variable importance for heterogeneous datasets.
ANN / deep learning	Captures complex nonlinear patterns when sufficient data are available.
NLP	Extracts information from literature and accelerates data compilation.
SVM / Gaussian process	Useful for smaller datasets and nonlinear regression.
Bayesian optimization	Searches for promising process windows with fewer experiments.
SHAP / explainable AI	Shows why a model makes predictions and which variables matter.

Ref: Wang et al. (2024); Li et al. (2025)

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Data Architecture for Biochar x AI

- Useful models require a full-chain dataset, not isolated measurements

Feedstock data	Carbonization data	Biochar properties	Application context	Performance targets
Biomass type, proximate / ultimate analysis, ash, lignin, cellulose, hemicellulose	Temperature, heating rate, residence time, gas atmosphere, activation / modification	pH, EC, surface area, pore size, functional groups, fixed carbon, stability	Soil, crop, contaminant, pH, dose, moisture, climate, management	Yield, adsorption capacity, SOC, N_2O, CO_2 removal, LCA, MRV indicators

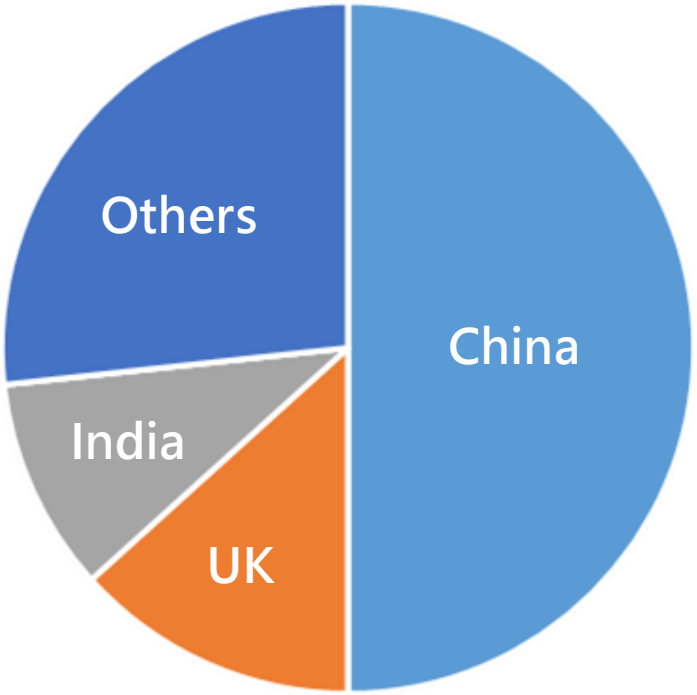
- **Key Principle:**

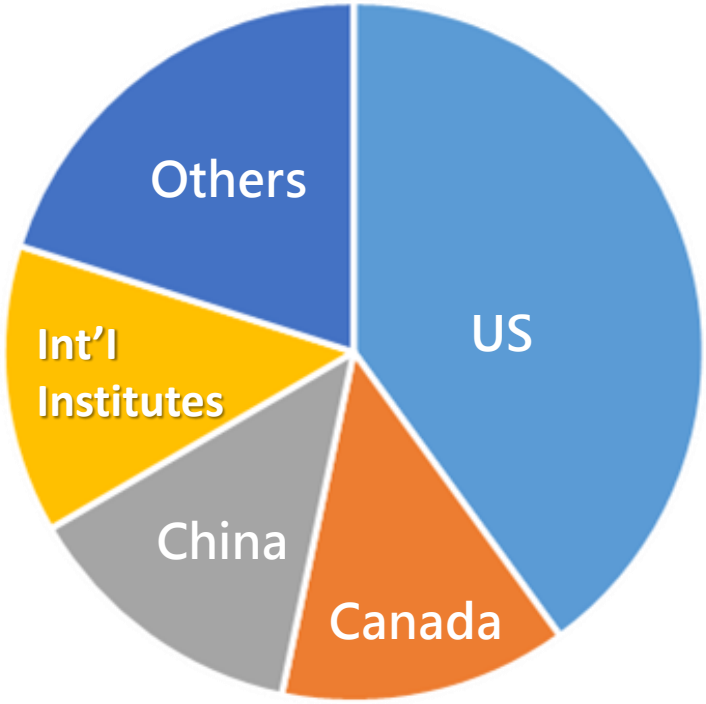
Standardize units, metadata, and boundary conditions before training models

Ref: Wang et al. (2024); Jiang et al. (2025)

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International Research Distribution of AI × Bioenergy (2021–2026)





(A) AI for Biomass Conversion

30 papers / reports

(B) AI for Biomass Supply Chain and Biorefinery Systems

15 papers / reports

Source: Journal articles, review papers, reports, and highly relevant research data from universities and international research institutes.

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AI Tools for Biomass Supply Chain Optimization

- **Key Message:** AI can support the development of cost-effective, reliable, and sustainable biomass supply chains.

AI / Optimization Tools	Potential Applications
GIS + Machine Learning	Biomass resource assessment and spatial mapping
CNN	Satellite and aerial image analysis
Random Forest / XGBoost	Feedstock availability, moisture, and cost prediction
Clustering	Feedstock classification and collection-area identification
Linear / Mixed-Integer Programming	Supply chain planning and logistics optimization
Genetic Algorithms / PSO	Storage location and transportation route optimization
Multi-objective Optimization	Balancing costs, emissions, supply reliability, and quality

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International Research Distribution of AI × Bioenergy

Key Findings

- The international research landscape indicates that AI × Bioenergy is **not dominated solely by traditional bioenergy-leading countries**. Instead, research is advancing rapidly in countries with strong data science capabilities, extensive experimental datasets, and active research in environmental engineering and carbon materials.
- **China** accounts for the largest share of publications, demonstrating particularly strong research activity in data-driven biomass conversion.
- **The United Kingdom** ranks second, with a stronger emphasis on methodological research, including Explainable AI (XAI).
- **European research** is more geographically distributed, with notable strengths in system integration and digital twin technologies.
- **The United States** has made significant contributions to the bioeconomy, biomass supply chains, and biorefinery systems.

Note: Recent shifts in U.S. energy research priorities may have led to the reclassification of bioenergy-related studies under broader categories, potentially resulting in an underestimation of U.S. research contributions.

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4. Applications of AI on Biochar Research

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Application (1): Predicting Biochar Yield and Properties

- **ML can link feedstock and process variables to targeted material performance:**
- **From empirical testing to predictive material design**

  - Typical inputs: biomass type, ash content, elemental composition, pyrolysis temperature, heating rate, residence time, and activation conditions.
  - Typical outputs: biochar yield, fixed carbon, pH, surface area, pore structure, CEC, and adsorption capacity.
  - Main value: screens feedstock–process combinations before extensive experiments.

Ref: Wang et al. (2024); Jiang et al. (2025)

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Application (2): Optimizing Carbonization Conditions

- **AI can search for operating windows that maximize function and carbon stability**

  - Optimization targets include high fixed carbon, aromaticity, surface functionality, CO_2 adsorption, and long-term stability.
  - Variables include temperature, residence time, heating rate, carrier gas, activation agent, and post-treatment.
  - Bayesian optimization and ML screening can reduce the number of experiments needed to reach target performance

- **Goal:**
  Design biochar for the intended use, not merely produce char.

Ref: Jiang et al. (2025); Li et al. (2025)

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Application (3): Carbon Sequestration Assessment

- **AI can support biochar design for carbon dioxide removal and long-term carbon storage**

Stability	NLP mining	CO_2 adsorption	Carbon accounting
Predict persistent carbon fraction and long-term storage potential.	Extract evidence from literature to accelerate model building.	Estimate capture potential from surface chemistry and pore properties.	Link production data, application records, and carbon-credit calculations.

- **Biochar carbon removal requires credible evidence:**

  Feedstock origin, process data, stability indicators, application records, and leakage / life-cycle boundaries

Ref: Li et al. (2025); Bai et al. (2026)

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Application (4): Biochar Adsorbents for Water Treatment

- **Adsorption capacity prediction is one of the most active Biochar x AI areas**

  - Biochar is being modeled for adsorption of heavy metals, dyes, nutrients, ammonia nitrogen, phosphorus, antibiotics, and emerging contaminants.
  - Input variables may include feedstock, activation condition, surface area, functional groups, solution pH, pollutant concentration, and contact time.
  - AI helps identify promising adsorbents and process conditions before full experimental screening.

Ref: Chang & Lee (2024); Liu et al. (2025)

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Application (5): Soil Amendment and Crop Production

- **Field response is variable.**
- **ML can help reveal patterns across soils, crops, and climates.**

- Biochar may influence soil pH, water retention, nutrient availability, microbial activity, soil organic carbon, and crop yield.
- The same biochar may perform differently across soil types, climates, crops, and fertilizer regimes.
- ML and meta-analysis can support location-specific recommendations and reduce N_2O mitigation uncertainty.

Ref: Zeng et al. (2025); Bai et al. (2026)

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Application (6): Biochar, N_2O and Yield-Scaled Climate Impacts

➢ **AI can help quantify both agronomic benefits and GHG mitigation.**

Crop yield	Soil organic carbon	N_2O emissions	Yield-scaled GWP
Production response to biochar-based fertilizers	Carbon storage improvement through biochar addition	Potential mitigation from improved nitrogen cycling and soil conditions	Climate impact per unit crop output

➢ **Interpretation for Research Design**

- Evaluate biochar benefits using both environmental and crop productivity indicators.
- Combine field trials, meta-analysis, and ML to improve generalization across regions.
- Use explainable models to identify conditions where biochar performs best.

Ref: Zeng et al. (2025); Bai et al. (2026)

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Digital MRV for Biochar Carbon Removal

- **AI can support monitoring, reporting, and verification across the biochar carbon chain.**

M	Monitoring	feedstock source, moisture, mass balance, pyrolysis parameters, biochar properties
R	Reporting	production records, application site, dose, stability indicators, LCA assumptions
V	Verification	carbon persistence, leakage, additionality, uncertainty, and audit-ready data

- **MRV value: Turn biochar from a material into a credible carbon-neutrality instrument.**

Ref: Li et al. (2025); Bai et al. (2026)

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5. Current Challenges

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Challenge (1): Data Quality and Standardization

- **AI performance depends on the completeness and comparability of biochar datasets.**

- Different studies report feedstocks, process conditions, and analytical results using inconsistent formats.
- Units, testing methods, activation protocols, and application conditions are often not harmonized.
- Missing metadata can make otherwise useful experimental data difficult to reuse.
- Standardized data templates are a prerequisite for practical AI deployment.

Minimum Dataset Elements

1) Feedstock identity and composition
2) Thermal process conditions
3) Biochar physicochemical properties
4) Application environment
5) Performance metric and uncertainty

Ref: Wang et al. (2024); Jiang et al. (2025)

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Challenge (2): Scale-Up and Field Validation

- **Laboratory models must be tested against pilot-scale and long-term field evidence.**

  - Many ML models are trained on laboratory-scale datasets, while pilot and industrial datasets are limited.
  - Field outcomes are affected by soil variability, weather, management practices, and time.
  - For carbon credits, long-term carbon persistence and uncertainty must be defensible.
  - A stronger bridge is needed between lab experiments, pilot systems, field trials, and carbon accounting.

Ref: Wang et al. (2024); Bai et al. (2026)

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Roadmap for AI Commercialization: From Research to Industrial Applications

Commercialization Barriers	Improvement Strategies
High feedstock variability	Standardized feedstock databases and quality monitoring
Insufficient industrial data	Long-term monitoring and industrial data collection
Poor model generalizability	Cross-feedstock and cross-site validation
Limited model interpretability	Explainable AI and hybrid modeling
Difficult integration with existing facilities	Phased implementation and digital integration
Uncertain return on investment	Techno-economic assessment and pilot demonstrations
Incomplete carbon accounting frameworks	Integration with standardized MRV and certification systems

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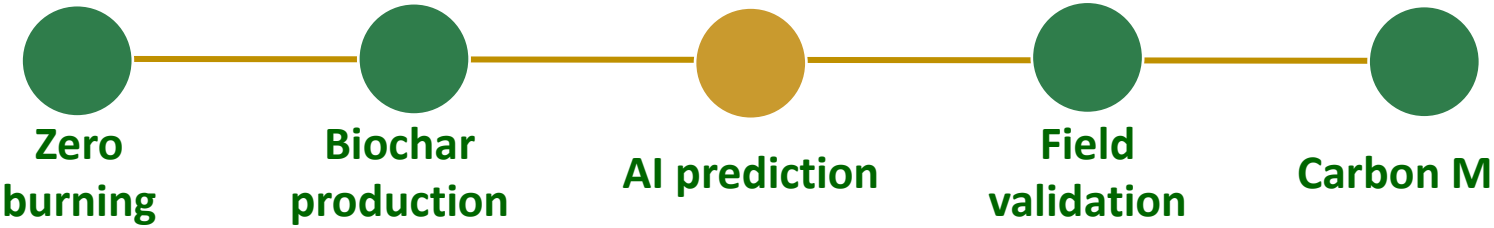
6. Future Actions

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Opportunity for Thailand and Carbon Neutrality

- **AI can connect agricultural residue management, $PM_{2.5}$ reduction, circular economy, and carbon removal.**

Local feedstocks	AI model targets	Deployment logic	Policy value
Rice straw, fruit tree branches, bamboo residues, wood waste, mushroom residues, and other agricultural biomass.	Optimal pyrolysis conditions, biochar stability, adsorption function, soil response, and GHG mitigation potential.	From zero-burning strategy to biochar production, field application, and carbon removal verification.	Supports carbon-neutral agriculture, rural circular economy, and data-based MRV for carbon credits.



- **Strategic Value:**
  Develop localized evidence rather than relying only on overseas biochar models.

Zero Burning + Biochar + AI

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Suggested Roadmap: Biochar x AI Platform

- **A practical program can be built in four stages:**

Stage 1	Stage 2	Stage 3	Stage 4
Build local dataset	Train models	Field validation	MRV integration
Feedstock, carbonization, biochar characterization, application data	Yield, surface area, stability, adsorption, soil response, N_2O	Compare model predictions with pilot and field trial results	Digital carbon accounting and decision-support dashboard

- **Roadmap Principle: Start with high-quality local data, then expand toward decision support and carbon verification.**

Ref: Jiang et al. (2025); Li et al. (2025)

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Suggested Research Design

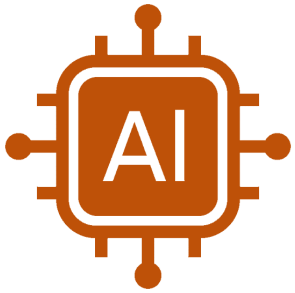
A Biochar x AI project should combine experiments, modeling, interpretation, and validation.

- Select priority feedstocks and define target applications: carbon removal, soil amendment, or water treatment.
- Generate standardized experimental data across controlled pyrolysis / activation conditions.
- Train multiple ML models and compare predictive accuracy, robustness, and interpretability.
- Use SHAP or feature importance to identify key drivers and guide next experiments.
- Validate predictions with pilot-scale production and field or application testing.

Model + Experiment loop:
AI should guide experiments, and new experiments should improve AI.

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Final Message



AI commercialization should follow a stepwise approach:

From reliable data collection and predictive analytics to decision support, system optimization, and integrated digital platforms.

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Biomass / Biochar x AI

Unsolved Problems Are Waiting……



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If I change, the whole world changes.



攝影：吳耿東，日本京都火車站（2005）

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Thank you for your attention.

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