Carbon Negative Biochar Systems Contribute to Sustainable Urban Green Infrastructure: A Critical Review

Sachini Supunsala Senadheera[a,b,1], Piumi Amasha Withana[a,b,1], Juin Yau Lim[a,b,c,1], Siming You[d],

Scott X. Chang[e], Fang Wang[f,g], Jay Hyuk Rhee[b,c], Yong Sik Ok[a,b,]*

[a] *Korea Biochar Research Center, APRU Sustainable Waste Management Program & Division of Environmental Science and Ecological Engineering, Korea University, Seoul, 02841, Republic of Korea*

[b] *International ESG Association (IESGA), Seoul, 06621, Republic of Korea*

[c] *School of Business Administration, Korea University, Seoul, 02841, Republic of Korea*

[d] *James Watt School of Engineering, University of Glasgow, G12 8QQ, UK*

[e] *Department of Renewable Resources, University of Alberta, 442 Earth Science Building, Edmonton, AB, T6G 2E3, Canada*

[f] *State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China*

[g] *University of Chinese Academy of Sciences, 100049 Beijing, China*

* Corresponding author: Yong Sik Ok, E-mail: yongsikok@korea.ac.kr

[1] These authors contributed equally to this study

Bibliometric analysis on biochar in green infrastructure

Indeed, a comprehensive examination encompassing aspects such as the number of publications, research focal points, methodologies employed, author distribution, and knowledge networks offers a macro-level understanding of the research landscape. A thorough analysis of 1897 papers with 5019 keywords collected from the "Web of Science" database based on the following search terms was carried out to obtain a comprehensive overview of the current application of biochar in green infrastructure.

(ALL=(Biochar)) AND ALL=("building" or "construction" or "infrastructure" or "green building" or "green infrastructure" or "stormwater" or "stormwater management" or "rain water" or "runoff" or "urban runoff" or "flood" or "rain garden*" or "urban planning" or "permeable pavement" or "green roof" or "vertical wall" or "green wall*" or "green facade*" or "cement" or "concrete" or "vertical greenery system*")

The VOSviewer software was used to visualize and analyze the collected data. VOSviewer is a powerful tool for bibliometric analysis that allows for creating visualizations such as co-authorship networks, keyword co-occurrence maps, and citation networks. This visualization approach enhances our understanding of the research landscape and facilitates the identification of key themes and areas for future exploration. Keyword clustering analysis categorizes and assesses the relationships between relevant keywords, enabling researchers to understand research progress and identify hot spots. The profile value of a cluster indicates its credibility, allowing researchers to prioritize areas of focus. This method provides a comprehensive overview of the field and helps identify emerging trends and research gaps. It guides resource allocation and facilitates a systematic exploration of the field's current state and future directions.

Collaboration and co-citation analyses conducted through the VOSviewer software showed that the number of papers has grown faster since 2010, with China, the United States, India, Australia, South Korea, Italy and Germany as the leading countries in this research area (Table S1). Regarding country collaboration analysis, the Chinese Academy of Sciences published the most papers, followed by the United States. China and the United States have indeed been significant contributors to research and development on a global scale in recent years. Both countries have made substantial investments in scientific research, technology development, and innovation, resulting in numerous collaborations with other nations. We can find more articles published and a high level of research in Asia in recent years, which is related to the fact that China and India, as large and populous countries, have significant agricultural sectors and generate substantial amounts of biomass and agricultural waste. This abundance of biomass resources can create research opportunities and interest in exploring biochar production and applications.

The literature on biochar applications in green infrastructure was distributed in a wide range of journals (534 journals), including Science of the Total Environment, Construction and Building Materials, Journal of Cleaner Production, Journal of Environmental Management, Chemosphere, Sustainability, and Bioresource Technology. This literature spans various disciplines such as environmental sciences, engineering, agriculture, materials science, construction building technology, and more. They cover topics including ecology, energy, water resources, urban studies, anthropology, toxicology, forestry, and construction, etc. These subjects represent a diverse range of research areas and academic fields.

The authors, Gupta S, Ok YS, and Garg A, have emerged as key contributors in biochar-green infrastructure applications, conducting pioneering research in exploring the potential of biochar in enhancing the performance and sustainability of green infrastructure systems.

Scientometric visualization of the top 200 keywords (from VOSviewer) showed that biochar production from feedstock, processes and applications (in red cluster which consists of keywords such as biochar, pyrolysis, gasification, climate change,biofuels, biomass pyrolysis, and etc.), the application of biochar in green infrastructure, green roof, stormwater management etc. (in green cluster including keywords runoff, green roof, green infrastructure, low impact development and etc.), the application of biochar in building construction/ cementitious applications (in yellow cluster with keywords such as carbon sequestration, carbon sink,carbonation, cement, cement mortar, cement-based composites, CO_2 capture, composites, composting, compressive strength, concrete,porosity, durability, filler, fracture energy, internal curing, mechanical properties, mechanical strength, mortar, permeability, pervious concrete, accelerated carbonation etc.), heavy metal adsorption (in blue cluster consisting of keywords adsorption, ammonium, cadmium, chromium, arsenic, heavy metals, immobilization, leaching, nitrates, nutrients, mercury, phosphate, water treatment, stabilization etc.) and biochar related soil properties (in purple cluster with keywords including microbial community structure, soil fertility, soil properties, yield, organic matter, biochar application, crop yield, and denitrification) (Figure S 1).
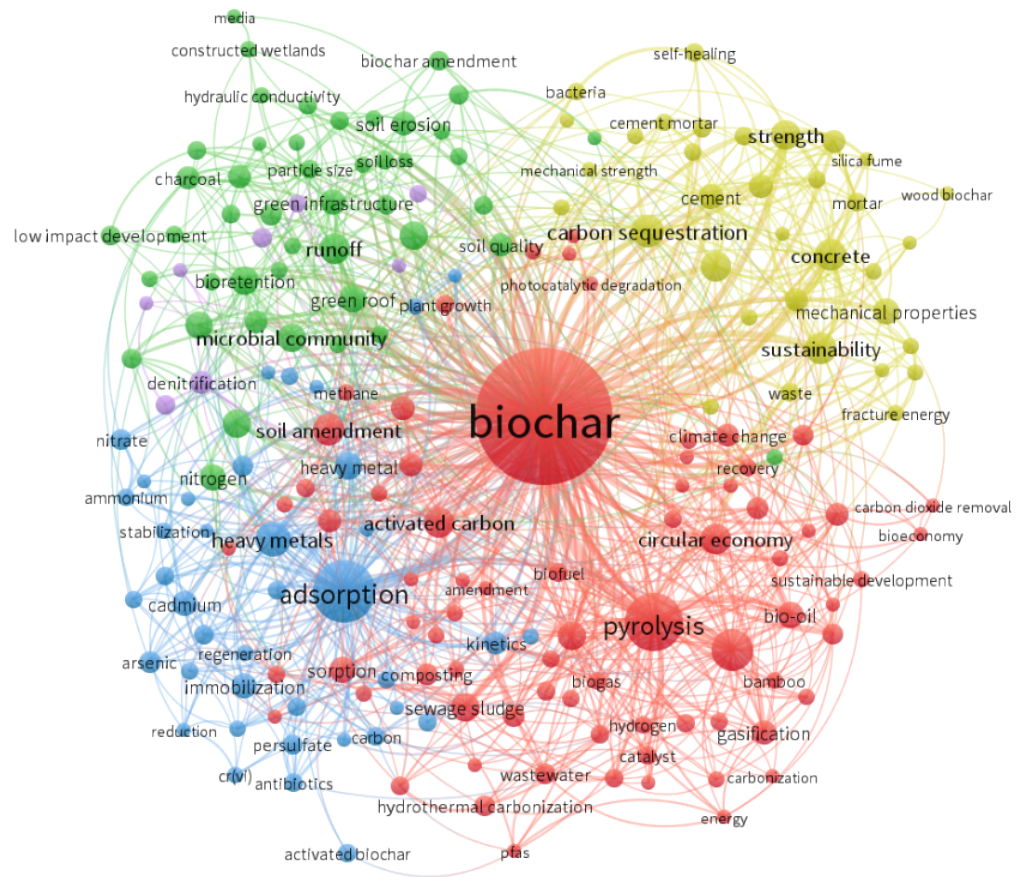
Figure S1: Scientometric visualization of the top 200 keywords related to biochar applications in green infrastructure.

First, "biochar" was the most common keyword, ranking first, followed by "pyrolysis", "adsorption" and "biomass". These three keywords are the basic terms for feedstock, method and application, representing the fundamentals in the biochar field. It provides readers with an understanding of the key topics and areas of focus within the context of the analysis.

Table S1: Countries producing most no. of publications

Countries/Regions	Record Count	% of 1,897
PEOPLES R CHINA	881	46.442
USA	353	18.608
INDIA	121	6.378
AUSTRALIA	113	5.957
SOUTH KOREA	95	5.008
ITALY	75	3.954
GERMANY	70	3.69
ENGLAND	60	3.163
CANADA	59	3.11
BRAZIL	47	2.478
PAKISTAN	47	2.478
SINGAPORE	41	2.161
POLAND	39	2.056
EGYPT	36	1.898
SPAIN	36	1.898
CZECH REPUBLIC	34	1.792
MALAYSIA	34	1.792
SWEDEN	34	1.792
SAUDI ARABIA	32	1.687
FRANCE	31	1.634
FINLAND	25	1.318
GREECE	25	1.318
DENMARK	24	1.265
IRAN	24	1.265
TAIWAN	23	1.212
NEW ZEALAND	22	1.16
PORTUGAL	21	1.107
JAPAN	20	1.054
SLOVAKIA	20	1.054
SCOTLAND	16	0.843
VIETNAM	16	0.843
NORWAY	15	0.791
COLOMBIA	14	0.738
MEXICO	14	0.738
NETHERLANDS	14	0.738
IRELAND	12	0.633
AUSTRIA	11	0.58
BANGLADESH	11	0.58
GHANA	11	0.58
NIGERIA	11	0.58
RUSSIA	11	0.58
SWITZERLAND	11	0.58
TURKEY	11	0.58
THAILAND	10	0.527
ETHIOPIA	9	0.474
SOUTH AFRICA	9	0.474

SRI LANKA	9	0.474
LITHUANIA	8	0.422
U ARAB EMIRATES	8	0.422
WALES	8	0.422
BELGIUM	7	0.369
ISRAEL	7	0.369
KAZAKHSTAN	6	0.316
NORTH IRELAND	6	0.316
PERU	5	0.264
ALGERIA	4	0.211
CHILE	4	0.211
ESTONIA	4	0.211
INDONESIA	4	0.211
SERBIA	4	0.211
SLOVENIA	4	0.211
TURKIYE	4	0.211
ARGENTINA	3	0.158
ECUADOR	3	0.158
HUNGARY	3	0.158
IRAQ	3	0.158
LATVIA	3	0.158
NEPAL	3	0.158
PANAMA	3	0.158
PHILIPPINES	3	0.158
QATAR	3	0.158
ROMANIA	3	0.158
TANZANIA	3	0.158
BOSNIA HERCEG	2	0.105
BOTSWANA	2	0.105
COSTA RICA	2	0.105
LAOS	2	0.105
LEBANON	2	0.105
MALTA	2	0.105
MONTENEGRO	2	0.105
MOZAMBIQUE	2	0.105
OMAN	2	0.105
SIERRA LEONE	2	0.105
UGANDA	2	0.105
BRUNEI	1	0.053
CAMEROON	1	0.053
CYPRUS	1	0.053
DEM REP CONGO	1	0.053
GRENADA	1	0.053
GUINEA	1	0.053
ICELAND	1	0.053
JORDAN	1	0.053
KUWAIT	1	0.053

KYRGYZSTAN	1	0.053
MOLDOVA	1	0.053
MOROCCO	1	0.053
PAPUA N GUINEA	1	0.053
TUNISIA	1	0.053
UKRAINE	1	0.053
UZBEKISTAN	1	0.053
YEMEN	1	0.053
2 record(s) (0.105%) do not contain data in the field being analyzed		