



REVIEW ARTICLE

Recent advances in biomass-derived materials for sustainable agriculture

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Abstract

The shift towards sustainable agriculture is vital for addressing pressing global issues, including food security, environmental harm and resource depletion. Materials derived from biomass present an innovative pathway to sustainability by leveraging renewable, biodegradable and cost-effective resources to boost agricultural output while reducing ecological impact. This review examines the wide-ranging potential of biomass-based materials, emphasising their roles in enhancing soil health, increasing crop yields and promoting integrated waste management. It also highlights recent progress in developing biochar, biopolymers and fertilisers, showcasing their roles in improving nutrient recycling, supporting carbon sequestration and decreasing reliance on synthetic agricultural inputs. Furthermore, the paper explores the contributions of advanced technologies such as pyrolysis and anaerobic digestion in maximising the efficient use of biomass. The review addresses obstacles like scalability, cost considerations and environmental challenges while offering policy recommendations and identifying key areas for future research. Ultimately, this comprehensive analysis underscores the significant impact of biomass-derived materials in driving sustainable agricultural practices and advancing a circular economy.

Keywords: agriculture; biomass; biomaterials; soil amendment; sustainability

Introduction

Sustainable agriculture is vital to meet the increasing global food demand by conserving energy and nature. Its focus is to practice soil fertility management, water conservation, reduce greenhouse gas (GHG) emissions and encourage biodiversity. Sustainable agriculture can mitigate climate change impacts, enhance food security and support farmer livelihoods (1). Biomass-derived materials play a fundamental role in progressing sustainable agriculture. These biomass materials can be transformed into valuable products like biofertilisers, biopesticides and other bioproducts (2). Biomass utilisation paves the way to waste reduction, mitigates environmental pollution and it enhances soil fertility and health to boost agriculture. The lignocellulosic biomass with high cellulose content improves nutrient retention and enhances crop-produce yield by conserving water and mitigating soil erosion (3). Biomass incorporation into farming systems directly or indirectly adopts a circular economy approach by reusing organic waste, reducing reliance on non-renewable resources and encouraging renewable energy production. Biomass utilisation as cover cropping and no-till farming contributes to soil nitrogen fixation, enhancing overall soil quality and helps retain soil structure and moisture by evicting fertiliser input (4). Furthermore,

biomass-derived materials contribute to carbon sequestration and climate change mitigation. When biomass is converted into bioenergy or biofuels, it releases carbon dioxide, but this is balanced by the carbon uptake during the growth by photosynthesis. As a result, the net carbon emissions from biomass energy are net zero, making it an eco-friendly substitute to fossil fuels (5).

The growing global adoption of sustainable agricultural practices is evident, with around 68 % of farmers incorporating crop rotation, 56 % adopting reduced or no-till methods and 38 % utilising biofertilisers, biocontrols or biostimulants. Additionally, 33 % of farmers globally are practising cover cropping to improve soil health and resilience against climate change. However, in India, the adoption of sustainable farming remains relatively low, with less than 4 % of farmers embracing these practices (6). Organic farming currently covers approximately 2.8 million hectares, representing only 2 % of the country's net sown area, while natural farming is rapidly expanding, with around 800000 farmers implementing this approach (7). Integrated pest management has been promoted for decades and now spans over 5 million hectares, whereas agroforestry and rainwater harvesting are practised across 25 million and 20-27 million hectares respectively (8). Despite these advancements, there is a need

for stronger policy support and awareness campaigns to accelerate the adoption of sustainable agricultural methods.

Biomass sources and their potential

Biomass serves as a crucial resource for sustainable agriculture, offering renewable alternatives to conventional inputs while promoting environmental conservation. Among the various biomass sources, crop residues, agricultural and agro-industrial wastes, forestry by-products play a significant role in enhancing soil health, generating bioenergy and supporting circular economy practices (9). A comprehensive view of the composition and potential applications of various residues, wastes and by-products is given in Table 1.

Crop residues

Crop residues, including straw, husks, stalks and leaves left after harvesting, are among the most abundant biomass sources. These residues viz., rice husk, wheat straw, sugarcane bagasse and maize stover can be effectively utilised for multiple applications including biochar production, composting and bioenergy generation. When properly managed, crop residues improve soil organic matter,

enhance nutrient availability and contribute to carbon sequestration (39). Instead of being burned, which leads to air pollution and greenhouse gas emissions, crop residues can be converted into biofertilisers or mulches to support sustainable farming practices.

Agricultural and agro-industrial wastes

Agricultural and agro-industrial wastes cover a wide range of organic materials generated during food processing and farming operations. These include fruit and vegetable peels, coffee husks, oilseed cakes and animal manure. Such wastes are valuable feedstocks for biogas production through anaerobic digestion, yielding renewable energy while reducing methane emissions. Additionally, agro-industrial by-products like molasses and bagasse are utilised in bioethanol and bioplastic production, reducing reliance on fossil-based materials (40). Converting these wastes into compost or bio-based fertilisers further enhances soil fertility, reducing the need for synthetic chemicals while promoting sustainable agricultural practices.

Forestry by-products

Forestry residues viz., sawdust, bark, wood chips and tree trimmings, offer significant potential for bioenergy production and soil

Table 1. Various biomass sources and its potential biomass-derived material

Category	Examples	Major composition	Biomass-derived material	Ref.
Crop residues				
Rice husk	Outer covering of rice grains	Cellulose, lignin, silica	Biochar, silica, biofuel, compost	(10)
Wheat straw	Dry stalks remaining after wheat harvest	Cellulose, hemicellulose, lignin	Biochar, bioethanol, paper pulp, mulching	(11)
Corn stover	Leaves, stalks and cobs left after corn harvesting	Cellulose, hemicellulose, lignin	Biogas, bioethanol, compost, biofuel	(12)
Sugarcane bagasse	Fibrous residue after sugarcane juice extraction	Cellulose, hemicellulose, lignin	Paper pulp, bioethanol, biogas, particle board, briquette	(13)
Groundnut shells	Outer shells of groundnuts/peanuts	Lignocellulose, protein, oils	Briquettes, activated carbon, biochar	(14)
Cotton stalks	Stems of cotton plants post-harvest	Lignin, cellulose	Particle board, paper pulp, briquette, pellets, biochar	(15)
Coconut husk	The fibrous outer shell of a coconut	Lignin, cellulose, tannins	Coir, biochar, fibreboard	(16)
Soybean straw	Stems and leaves left after soybean harvesting	Cellulose, hemicellulose, proteins	Bioethanol, compost	(17)
Sorghum stalks	Stems remaining after grain harvest	Cellulose, hemicellulose, lignin	Biogas, paper pulp, pellets, biochar, biopolymer	(18)
Barley straw	Residue from barley crop	Cellulose, lignin	Bioplastics, bioethanol, biogas	(19)
Agricultural and agro-industrial wastes				
Fruit and vegetable peels	Waste from food processing industries	Pectin, cellulose, antioxidants	Bioactive compounds, compost, bioplastics	(20)
Spent coffee grounds	Residue from the coffee brewing process	Cellulose, lignin, caffeine, polyphenols	Biochar, biogas, cosmetics	(21)
Palm oil mill effluent	Liquid waste from palm oil processing	Water, organic acids, oil residues	Biogas, fertiliser, wastewater treatment	(22)
Brewery waste	Residue from beer production	Proteins, fibre, carbohydrates	compost, biofuel	(23)
Dairy waste	Residue from milk and cheese processing	Lactose, proteins, whey	Biogas, probiotics	(24)
Cassava peels	Outer layer of cassava tubers	Starch, fibre, cyanogenic glycosides	Bioethanol, compost, biopolymer	(25)
Molasses	A by-product of sugar production	Sugars, organic acids	Bioethanol	(26)
Vinasse	Waste liquid from ethanol distillation	Potassium, organic acids, carbohydrates	Fertiliser, biogas, wastewater treatment	(27)
Press mud	Solid waste from sugarcane juice clarification	Organic matter, calcium phosphate	Fertiliser, compost, biogas	(28)
Tea waste	Residue from tea processing	Polyphenols, tannins, fibre	Compost, antioxidants	(29)
Spent grain	Solid residue from beer brewing	Protein, fibre, carbohydrates	Bioethanol, compost	(30)
Fish processing waste	Heads, bones, scales and viscera from fish industry	Proteins, oils, collagen	Fish meal, gelatin, biodiesel, fertilisers	(31)
Forestry by-products				
Sawdust	Fine particles from wood cutting	Cellulose, lignin, hemicellulose	Biochar, briquettes, particle board	(32)
Wood chips	Small wood fragments from logging or sawmills	Lignin, cellulose, hemicellulose	Biofuel, paper pulp	(33)
Bark	The outer protective covering of trees	Tannins, lignin, cellulose	Tannin, compost, adhesives	(34)
Tree pruning waste	Branches, twigs and leaves from pruning	Cellulose, lignin, minerals	Compost, biochar	(35)
Pulp and paper mill sludge	Residue from the pulp and paper industry	Cellulose, minerals, organic matter	Biogas, wastewater treatment	(36)
Pine needles	Leaves from pine trees	Resin, cellulose, terpenes	Essential oil extraction, biofuel	(37)
Bamboo residues	Waste from bamboo processing	Cellulose, hemicellulose, lignin	Bio-composites, biochar, paper pulp	(38)

enrichment. These by-products, often generated from logging, wood processing and forest maintenance, can be converted into biochar, wood pellets or briquettes for renewable energy applications. Additionally, forestry residues serve as a raw material for biodegradable packaging and eco-friendly mulching solutions (41). Proper utilisation of these by-products not only minimises environmental waste but also supports carbon sequestration and enhances soil moisture retention in agricultural systems.

By utilising crop residues, agro-industrial wastes and forestry by-products effectively, agricultural systems can transition toward a circular economy model, promoting long-term environmental and economic benefits.

Applications of biomass-derived materials in agriculture

Biomass-derived materials offer sustainable solutions for modern agriculture, addressing challenges related to soil health, crop productivity and waste management. By converting organic residues into valuable agricultural inputs, these materials contribute to a circular economy, reduce dependence on synthetic chemicals and enhance environmental sustainability (42). The biomass-derived materials, their applications in agriculture and associated impacts are shown in Table 2.

Biochar, produced from the pyrolysis of crop residues and forestry by-products enhances soil porosity, increases water retention and acts as a carbon sink. Compost derived from agricultural and agro-industrial waste augments the soil with essential nutrients and promotes microbial diversity, leading to improved nutrient cycling. Additionally, bio-based mulches made from plant residues help regulate soil temperature, prevent erosion and suppress weed growth, thereby creating a more favourable environment for plant growth (48).

Biomass-derived materials contribute to increased crop yields by improving nutrient availability and plant health. Organic fertilisers, including biofertilisers and composted plant residues, supply essential macronutrients and micronutrients in a slow-release form, reducing the risk of nutrient leaching and soil degradation. Biopesticides and plant-derived bio-stimulants, extracted from agro-industrial by-products enhance plant resistance against pests and diseases while promoting root development and overall plant vigour. Additionally, biodegradable seed coatings made from biomass help improve seed germination rates and protect young plants from environmental stresses (49).

The conversion of agricultural waste into valuable products is a key strategy for promoting sustainable farming practices.

Table 2. Different biomass-derived materials and their utilisation

Derived biomaterials	Application in agriculture	Purpose of application	Crop yield impact	Benefits	Demerits	Ref.
Biochar	Soil amendment, carbon sequestration	Enhances soil fertility, improves water retention	Increases yield by 10 %-20 %	Improves nutrient retention, reduces GHG	High production cost, variability in properties	(43)
Bio-polymers	Biodegradable mulch films, controlled-release fertilisers	Reduces soil moisture loss, minimises agrochemical runoff	Improves plant growth and germination	Reduces pollution, improves soil structure	The decomposition rate may vary and the initial cost is high	(44)
Lignin-based bio-stimulants	Crop growth enhancers, stress tolerance improvement	Stimulates plant growth and increases stress resistance	Yield improvement varies with crop	Eco-friendly alternative to synthetic stimulants	Limited studies on long-term effects	(45)
Bio-fertilisers	Nitrogen fixation, phosphate solubilisation	Enhances nutrient availability, reduces synthetic fertiliser use	Increases yield by 15 %-25 %	Improves soil microbiota, cost-effective	Requires proper handling and storage	(46)
Anaerobic digestate	Organic fertiliser, soil conditioner	Supplies of essential nutrients enhance microbial activity	Varies depending on nutrient composition	Reduces waste disposal, promotes circular economy	Risk of heavy metal contamination if not treated properly	(47)

Biomass-derived materials facilitate efficient waste valorisation by transforming organic residues into bioenergy, bio-based chemicals and agricultural inputs. Anaerobic digestion of livestock manure and agro-industrial waste produces biogas, a renewable energy source that can replace fossil fuels for farm operations (50). Simultaneously, the digestate from biogas plants serves as an organic fertiliser, closing the nutrient loop in agricultural systems. Additionally, lignocellulosic biomass from crop residues and forestry waste can be used to manufacture biodegradable packaging materials, reducing plastic waste and promoting eco-friendly agricultural supply chains. These sustainable applications not only support resilient farming systems but also contribute to global efforts toward climate change mitigation and resource-efficient agriculture.

Advancements in biomass-derived products

The development of biomass-derived products has revolutionised sustainable agriculture by providing eco-friendly alternatives to conventional farming inputs. These advancements contribute to soil health, nutrient efficiency and waste valorisation while reducing environmental impact. Among the most promising innovations are biochar, biopolymers and fertilisers, each offering unique benefits for improving agricultural sustainability.

Biochar and its multifunctional benefits

Biochar, a carbon-rich material formed through the pyrolysis of biomass, has gained significant attention for its multifunctional applications in agriculture. When incorporated into the soil, biochar enhances water retention, improves aeration and increases nutrient-holding capacity, leading to better crop growth and resilience. Additionally, it acts as a carbon sink, helping mitigate climate change by sequestering atmospheric CO₂. Biochar also serves as a carrier for beneficial microbes, promoting soil microbial diversity and enhancing plant health. Moreover, its ability to reduce the leaching of nutrients like nitrogen and phosphorus makes it an effective soil amendment for long-term fertility improvement (51).

Biopolymers for sustainable inputs

Biopolymers derived from biomass such as starch, cellulose and lignin are increasingly being used as sustainable agricultural inputs. These materials are biodegradable and serve as alternatives to synthetic plastics in applications like controlled-release fertilisers, seed coatings and mulch films. Biopolymer-based coatings improve seed germination and early plant establishment by providing a protective barrier against pathogens and environmental stressors. In addition, biodegradable mulch films reduce soil moisture loss,

suppress weed growth and eliminate the need for plastic removal, thus minimising environmental pollution (52).

Biofertilisers and nutrient recycling

Biofertilisers, derived from microbial cultures and organic biomass, play a crucial role in nutrient recycling and soil fertility management. These formulations, containing nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azospirillum*), phosphate-solubilizing microorganisms and mycorrhizal fungi enhance plant nutrient uptake and reduce dependence on synthetic fertilisers. Composting of agricultural residues, along with microbial inoculation, accelerates organic matter decomposition and enriches soil with essential nutrients. Additionally, anaerobic digestion of biomass produces nutrient-rich digestate, which serves as an organic fertiliser, closing the nutrient cycle and reducing waste accumulation. The integration of biofertilisers into farming systems not only boosts crop yields but also improves soil health and long-term sustainability (53).

The continuous advancements in biomass-derived products are driving the transition toward environmentally responsible agricultural practices. By utilising biochar, biopolymers and biofertilisers, farmers can enhance productivity, reduce environmental degradation and contribute to a circular bioeconomy, ensuring a more resilient and sustainable food system.

Technological innovations in biomass utilization

Advancements in biomass processing technologies such as pyrolysis, anaerobic digestion and emerging valorisation techniques are driving the transition toward sustainable agriculture by enabling the efficient conversion of organic residues into valuable products.

Pyrolysis technologies for biochar production

Pyrolysis is a thermochemical process that converts biomass into biochar, bio-oil and syngas under limited oxygen conditions. Recent advancements in pyrolysis technologies have improved biochar yield and quality, optimising its application in agriculture. Slow pyrolysis, operating at lower temperatures (300 °C–700 °C), is particularly effective in producing stable biochar with high carbon content, enhancing soil fertility and water retention. Advanced techniques such as microwave-assisted and catalytic pyrolysis enable better control over biochar properties, increasing its nutrient-holding capacity and adsorption potential (54). Additionally, integrated pyrolysis systems now utilise bio-oil and syngas for energy production, improving the overall sustainability and economic feasibility of biochar production.

Anaerobic digestion for biogas and digestate

Anaerobic digestion is a biological process that breaks down organic biomass in oxygen-free conditions, producing biogas and digestate, a nutrient-rich by-product. High-rate anaerobic digesters such as

upflow anaerobic sludge blanket (UASB) and anaerobic membrane bioreactors, increase methane production while reducing retention time. The use of pre-treatment methods including thermal, enzymatic and hydrothermal processes further enhances biodegradability and gas yields. Digestate from biogas plants serves as an organic fertiliser, closing nutrient cycles and reducing reliance on chemical inputs in agriculture (55).

Emerging technologies for biomass valorisation

Innovative biomass valorisation technologies are unlocking new possibilities for converting agricultural residues into high-value products. Hydrothermal carbonisation (HTC) is an emerging technique that processes wet biomass under high temperatures and pressure to produce hydrochar, a material like biochar but with enhanced nutrient availability. Gasification, another promising approach, converts biomass into syngas, which can be used for electricity generation or as a feedstock for biofuels and green hydrogen production. Additionally, biorefinery approaches integrate multiple conversion pathways, utilising lignocellulosic biomass for bio-based chemicals, bioplastics and advanced biofuels. Enzymatic and microbial innovations are further enhancing the production of bio-based polymers and bio-stimulants, supporting sustainable agricultural inputs (56). The different biomass sources, the derived biomaterials, their conversion processes, yield and agricultural applications are summarised in Table 3.

Technological advancements in biomass utilisation are paving the way for more efficient, eco-friendly agricultural systems. By integrating pyrolysis, anaerobic digestion and emerging biomass valorisation techniques, sustainable agriculture can benefit from improved soil health, renewable energy generation and reduced environmental impact, contributing to a more resilient and resource-efficient food production system.

Challenges and limitations

Despite the utilisation of biomass-derived materials in sustainable agriculture, several challenges and limitations hinder their large-scale adoption. Key issues include the scalability and cost-effectiveness of production, environmental and social trade-offs and policy and regulatory constraints that impact commercialisation and implementation. One of the primary challenges in biomass utilisation is the scalability of production processes while maintaining cost-effectiveness. Technologies such as pyrolysis, anaerobic digestion and biorefining require a substantial initial investment in infrastructure, equipment and skilled labour (62). Additionally, variations in biomass availability, seasonal fluctuations and transportation logistics further impact the feasibility of large-scale deployment. The economic viability of biochar, biofertilisers and biopolymers depends on optimised production pathways, cost

Table 3. Biomass conversion method and its uses

Process of conversion	Biomass	Biomaterial derived	Yield (%)	Uses in agriculture	Ref.
Pyrolysis (slow or fast)	Crop residues (rice husk, wheat straw, corn stover)	Biochar	25 %–35 %	Soil amendment, carbon sequestration, nutrient retention	(57)
Biochemical extraction and polymerisation	Agricultural waste (sugarcane bagasse, fruit peels)	Biopolymers (starch-based bioplastics)	Varies	Biodegradable mulch films, controlled-release fertilisers	(58)
Hydrolysis and enzymatic treatment	Forestry by-products (wood chips, sawdust)	Lignin-based bio-stimulants	10 %–20 %	Enhancing plant growth, improving stress resistance	(59)
Microbial fermentation and enrichment	Animal manure and organic waste	Biofertilizers (<i>Rhizobium</i> , <i>Azospirillum</i>)	Depends on the microbial count	Nitrogen fixation, phosphate solubilisation, soil enrichment	(60)
Anaerobic digestion (biogas production)	Agro-industrial waste (palm oil mill effluent, dairy waste)	Anaerobic digestate	30 %–40 % (solid digestate)	Organic fertiliser, soil conditioner, microbial activity enhancement	(61)

reductions in processing technologies and efficient supply chain management. Without significant advancements in production efficiency and financial incentives, widespread adoption remains constrained, particularly in low-income and developing regions. While biomass-derived materials contribute to environmental sustainability, their large-scale production may pose unintended ecological and social challenges (63). Excessive extraction of agricultural residues for biochar or bioenergy can lead to soil degradation, nutrient depletion and reduced organic matter replenishment. Improper waste management during biomass processing may generate pollutants such as volatile organic compounds (VOCs) and particulate matter, affecting air quality. Social concerns also arise when land use shifts toward biomass production, potentially competing with food crops and leading to land tenure conflicts. Ensuring sustainable biomass sourcing and implementing circular economy principles are critical for minimising these trade-offs and achieving long-term benefits (64). By improving production efficiency and minimising ecological risks, biomass-derived materials can become a cornerstone of sustainable agriculture, contributing to global food security and environmental resilience.

Policy framework and future directions

The successful integration of biomass-derived materials into sustainable agriculture requires a well-defined policy framework, strategic research priorities and effective scaling-up strategies. Strengthening regulations, incentivising research and promoting large-scale adoption will enhance the economic viability and environmental sustainability of biomass utilisation in agriculture.

Policy recommendations for biomass integration

Developing comprehensive policies for biomass-derived materials is crucial for their widespread adoption in agriculture. Governments should establish clear guidelines for biochar application, biopolymer certification and biofertiliser standards to ensure safety, efficacy and market acceptance. Subsidies and financial incentives such as tax reductions and carbon credits can encourage farmers and industries to invest in biomass technologies. Integrating biomass utilisation into national sustainability programs such as climate action plans and circular economy initiatives will further promote its role in reducing carbon emissions and enhancing soil health. Additionally, policies should support decentralised biomass processing units in rural areas, improving access to renewable agricultural inputs and reducing dependence on fossil-fuel-based fertilisers and pesticides (65).

Research priorities for sustainable biomass utilization

Future research should focus on optimising biomass conversion technologies to improve efficiency, cost-effectiveness and environmental impact. Advancements in pyrolysis, anaerobic digestion and biorefining can enhance the quality and functionality of biochar, biofertilisers and biopolymers. Additionally, research into novel biopolymer formulations and biodegradable alternatives to synthetic agrochemicals will support the transition toward eco-friendly agricultural practices. Digital tools such as artificial intelligence (AI) and remote sensing can also be leveraged to monitor biomass availability, optimise resource allocation and improve decision-making in biomass utilisation strategies (66).

Strategies for scaling up adoption in agriculture

To achieve large-scale adoption of biomass-derived materials, coordinated efforts from policymakers, researchers and industry

stakeholders are required. Establishing demonstration farms and pilot projects will provide farmers with practical insights into the benefits of biomass-based amendments. Public-private partnerships can drive innovation, facilitate knowledge transfer and accelerate commercialisation by linking research institutions with industry players. Strengthening extension services and farmer training programs will improve awareness and capacity-building, ensuring efficient and sustainable biomass application. Additionally, integrating biomass utilisation with precision agriculture techniques can enhance resource efficiency, optimise nutrient management and maximise agricultural productivity (67).

By aligning policy initiatives, research advancements and implementation strategies, biomass-derived materials can play a transformative role in sustainable agriculture. Addressing existing barriers and leveraging emerging opportunities will contribute to resilient farming systems, climate change mitigation and a more sustainable global food supply chain.

Conclusion

Biomass-derived materials offer a transformative approach in enhancing agricultural sustainability by providing eco-friendly alternatives to conventional inputs. Through biochar, biopolymers and biofertilisers, these materials contribute to improved soil health, enhanced crop productivity and efficient waste management. Technological innovations such as pyrolysis and anaerobic digestion have further optimised biomass conversion into valuable products, promoting a circular economy in the agricultural sector. However, challenges related to scalability, cost-effectiveness and policy support must be addressed to unlock their full potential (68).

Looking ahead, a sustainable and circular agricultural future depends on integrating biomass-based solutions with precision farming, climate-smart agriculture and policy-driven incentives. Strengthening research efforts, fostering public-private partnerships and implementing supportive regulatory frameworks will accelerate the adoption of biomass-derived materials. By embracing these innovations, agriculture can transition toward a low-carbon, resource-efficient system that ensures food security while mitigating environmental impact. The path forward requires a collective commitment from policymakers, researchers, industry stakeholders and farmers to create a resilient and sustainable agricultural landscape for future generations.

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Authors' contributions

GJ involved in collection of literature and writing the manuscript; SS involved in conceptualization of idea; PV involved in writing the manuscript; DR & SK involved in review, editing and supervision. All authors read and approved the final manuscript.

Compliance with ethical standards

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