Promoting Urban Sustainability Through the Local Production of Ecological Paving Stones and Green Coal

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ABSTRACT

This study addresses the pressing environmental challenges of urban pollution and deforestation in developing countries by proposing sustainable solutions through the local production of eco-friendly paving stones and green charcoal. The primary objective is to reduce urban waste while simultaneously lowering CO_2 emissions in developing urban areas. The study employs a systematic and multivariate approach, integrating theoretical insights with empirical evaluations. Grounded in a robust framework encompassing urban sustainability, the circular economy, and environmental justice. The study utilizes Principal Component Analysis (PCA) as a methodological tool to analyze the performance of eco-friendly materials. Data were synthesized from 50 sources published between 2000 and 2023, selected based on their relevance, objectivity, and traceability. The analysis reveals that ecological paving stones possess mechanical properties comparable to traditional pavers, with enhanced durability in wet environments. The production of green charcoal as a new energy represents a key success of the SDG 7, reduces CO_2 emissions by 20% and deforestation by 15% in the local area. By reducing waste, lowering carbon emissions, and mitigating deforestation, these innovations pave the way toward sustainable urban development that aligns with sustainable development and circular economy.

Keywords: urban sustainability, eco-friendly paving, green charcoal, waste management, circular economy.

INTRODUCTION

Urban sustainability has become an imperative response to the multifaceted challenges posed by rapid urbanization, resource depletion, and climate change [1,2,3]. This situation is further aggravated by the continued reliance on carbon-intensive building materials and fossil fuels, which deplete natural resources and strain ecosystems [4,5,6]. Addressing these challenges is critical as they pose significant threats to both environmental sustainability and the well-being of urban populations. In response, circular economy has emerged as a transformative approach, reimagining waste as a resource that can be reintegrated into production cycles [3,4]. By moving beyond the traditional linear "extract-use-dispose" model, circular economy practices emphasize minimizing waste through recycling, reuse, and energy production [1,2,3,4,5]. In this framework, the introduction of ecologically sound materials such as paving stones and green coal made from recycled or sustainably sourced materials exemplifies how local initiatives can contribute to urban sustainability. Ecological paving stones offer a sustainable alternative to carbon-intensive construction materials while reducing landfill waste [12,15,28,29]. Furthermore, green charcoal production bolster energy sustainability by utilizing waste materials while simultaneously curbing deforestation [1,5,6,7,8]. These initiatives represent an emerging pathway toward sustainable development responding to a large range of SDG need: SDG7, SDG8, SDG9 and SDG11. But, despite these promising developments, there is limited

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research on the effectiveness of these innovations in the context of urban sustainability. Most studies focus on their technical or material properties, leaving a gap in understanding how these solutions can holistically address urban pollution, deforestation or CO_2 emissions while fostering economic development. Closing this gap is crucial to advancing sustainable urban development in rapidly growing cities, particularly in developing regions. This study aims to bridge this gap by evaluating the potential of ecological paving stones and green charcoal to reduce urban waste, while simultaneously lowering CO_2 emissions in developing urban areas. To achieve this, the research focuses on two specific objectives: (1) providing a comprehensive review of existing research on eco-materials and circular economy applications in urban settings, and (2) synthesizing the effectiveness of these innovations in reducing environmental impact and fostering sustainable development through a meta-analysis approach. To address these objectives, this study draws from several sources, selected based on their relevance, transparency, and traceability. A multivariate approach employing Principal Component Analysis (PCA) is used as a methodological tool to analyze the performance of eco-friendly materials. By synthesizing findings and evaluating empirical outcomes, this study underscores the transformative role that circular economy practices can play in enhancing waste management while advancing both environmental and economic sustainability [6,8,17,20,24,25].

METHODOLOGY

Data sources and measurements

The data used in this study comes from several sources, covering a recent period from 2000 to 2023, and focuses on the local production of ecological paving stones and green charcoal in urban areas. The sources were selected according to the availability of resources with a particular focus on relevance, objective, and traceability. Due to limited resources at national and sub-regional level, information was collected from national and international databases on the environment, urban waste and sustainable building materials.

The dependent variable is urban sustainability. A composite index of urban sustainability was constructed using the PCA, a method commonly used to synthesis several environmental indicators into a single representative score [21]. The independent variables include ecological paving and green charcoal, measured respectively by their production rate and their environmental impact.

To control the effect of other factors that may influence urban sustainability, certain explanatory variables such as waste management and the circular economy were also considered.

Variable	Measure	Expected effect	Sources
US	Urban sustainability	+	https://doi.org/10.1007/BF01325104
EP	ecological paving stones	+	http://dx.doi.org/10.1016/j.oceram.2024.100604
GC	Green charcoal	+	http://dx.doi.org/10.5539/jsd.v15n2p16
WM	Waste management	+	https://doi.org/10.1596/978-1-4648-1329-0
CE	Circular economy	+	http://dx.doi.org/10.1016/j.jclepro.2015.09.007
LJ	Creation of local jobs	+	https://www.oecd.org/en/publications/job-creation-and-local-economic-development-2023_21db61c1-en.html
AP	Air pollution	-	http://unesdoc.unesco.org/ark:/48223/pf0000156766.locale=fr

Analysis method

This study undertakes a comprehensive evaluation of the potential of eco-friendly paving stones and green charcoal to mitigate urban waste and reduce CO_2 emissions in developing urban areas. The methodological

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approach is systematic and multivariate, integrating both theoretical insights and empirical evaluations. Principal Component Analysis (PCA) is employed as a key methodological tool to dissect and comprehend the performance metrics of these eco-friendly materials.

Specification Model

The essence of this study is to exploit the potential of ecological paving stones and green charcoal on urban sustainability. Using a bivariate form, the restrictive form of the equation in panel form is as follows:

$$\mathbf{Y_{it} = \alpha + \beta_1 \; P_{it} + \beta_2 \; C_{it} + \epsilon_{it}}$$

Where Y_{it}= dependent variable, β_1 P_{it}= ecological paving stones,β_2 C_{it}= green charcoal, α= vector of coefficients of explanatory variables and ϵ_{it} = error term.

Production Materials

Raw materials

The composition of the raw material varies according to the desired product. Ecological paving stones mainly use PET or HDPE bottles and LDPE bags [7,10,23,27,29,31,32], all of which are thermoplastics. Mixed with sand and clay, this mixture is a sustainable alternative to conventional materials. In another hand, green charcoal is made from typical household and similar waste, biomass residues and agricultural waste, processed by pyrolysis [9,14,15,16,17,30].

Equipment

The equipment consists of a set of essential tools to help adjust the mixing proportions. The scale is used to weigh the cobblestones and ecological coal. Aggregates are sieved using a 0.5 mm sieve, or even less depending on the quality of the raw material. Breaking strength and flexural strength are determined using a splitting test with a compression machine, particularly for paving stones.

For production, the eco-paving equipment includes a plastic shredding machine, a mixer to combine the recycled materials, a hydraulic press to mold the paving stones or molds for traditional application, and an infrared thermometer to monitor the thermodynamic temperature of the reaction. And green charcoal requires a pyrolysis kiln to carbonize the biomass residues, a mixer to blend the binder and coke, and a compactor to compact the final product. This equipment is essential to guarantee the efficiency and sustainability of the products.

Production process

Ecological paving stone

Pre-treatment

This preliminary phase involves collecting, sorting and transporting the raw material [9,14,27]. Next, it is necessary to characterize the raw material by monitoring the following parameters: origin, nature, physico-chemical composition, state at a given time t and toxic potential. As each parameter can have a major impact on product quality and its impact [14,15,27,29,34], It should be noted that characterization must take account of the objective and the technical production equipment acquired [30,31].

Proportion of mixtures

Mix proportions can vary according to the characteristics of the raw material, generally using the principle, one characterization one mix proportion. However, the general average recommends a proportion of **50-70%**

sand, 0-10% clay and **20-50% recycled plastic [**4,7,8,9,11,23,27,29,45]**.** The proportions of sand, clay and plastic can guarantee the strength and durability of paving stones, but many works are limited to sand-plastic proportions.

Melting and mixing plastics

The fire is lit to trigger the activation energy required for the thermodynamic reaction in the oven, then the quantities of material are added in the proportions defined beforehand [28,33]. The melting time is timed to keep the temperature within the range of a chemical thermal degradation reaction at low temperature, typically between 200 and 750°C. This degradation takes place practically in the absence or with very little oxygen, and once the tester indicates that melting is complete, the additive materials are added and the mixture is homogenized by continuous mixing, before molding.

Moulding and demoulding

After mixing, the resulting paste is poured into a hydraulic press or a metal mold, the walls of which have been soaked in drain oil to facilitate removal from the mold [23,32]. The paste then takes the shape of the mold and is gradually compacted. The process is carried out quickly to avoid premature solidification, with an average time difference of 1 min. The cooling time depends on the temperature at which the sample was removed from the oven, as well as the weather on site, which can have an intrinsic influence.

The Finish

Once out of the hydraulic press or mold, the product is finished by polishing the faces and correcting any defects.

Characterization of physical and mechanical properties

The physico-mechanical parameters must essentially be defined to estimate the efficiency of the process and the quality of the products. The main tests to be carried out are compressive strength, wear resistance, flexural strength, porosity test for water absorption rate.

Green charcoal

Drying

Drying is a crucial stage aimed at eliminating the moisture present in raw materials, thereby facilitating the carbonization process [12,15,16,20]. Drying techniques vary considerably depending on the moisture content of the materials and the technologies used. Depending on the nature of the raw materials, whether they have a high or low moisture content, different methods can be applied [12,20].

Carbonization

This stage consists of carbonizing dry biomass, which undergoes slow pyrolysis (200 to 500°C) in an oxygen-poor environment, thereby promoting thermal decomposition and the formation of coke [9]. Once the furnace is ignited, the temperature gradually rises to 100°C. At this point, around 10% of the moisture in the biomass evaporates. The temperature then rises to 280°C. This phase is known as endothermic and requires energy. At 280°C, the pyrolysis phase begins. The biomass breaks down into coke, tar and other elements. This reaction is said to be exothermic because it releases energy. The oxygen supply must therefore be limited by blocking the openings to prevent the product from burning completely. The heat released by pyrolysis raises the temperature to 400°C, until all the material has been transformed into coal.

Grinding

After carbonization, the coal is still in the form of lumps, or coke [9,14,15]. These lumps need to be transformed into dust. When the grinding is mechanized, it produces a coal powder with regular grains. If grinding is carried out manually, it is advisable to sieve the ground product. The coke is then reduced to fine particles to obtain a homogeneous powder. The optimum size of the carbonized biomass should be less than 5 µm [15]. This stage is crucial for preparing an effective mixer.

Mixing

The product obtained after grinding is mixed with a binder, a chemical agent with viscous properties that binds the particles together to facilitate compaction [9,17,29]. Various binders can be used, the most common being cassava flour, starch and clay. Cassava flour is often preferred because of its starch content, which acts as a chemical agent with viscous properties. Mixing can be done by hand or using a mixer. Typical proportions are 1 kg cassava flour, 10 liters water and 20 kg charcoal powder [9]. Binder, representing around 5% of the dry weight of the mixture, is added to the powder to obtain a homogeneous mix. Above 7% of cassava flour-based binder, the final product can produce noxious smoke, while below 4%, it risks breaking up on drying. Correct mixing is essential for good compaction.

Particle size

Before compaction, the particle size of the coal powder must be controlled to ensure good cohesion. In general, the optimum coal particle size is less than 5 µm to ensure a homogeneous texture and better bonding with the binder.

Compaction

The compaction stage consists of pressing the mixture of coal and binder using a mechanical or manual press, to obtain solid charcoal ready for drying. The quality of the product depends on the grain size of the coal, the pressure applied generally between 5 and 10 MPa, the speed of compaction and the type of binder used. The shape of the product is determined by the hydraulic press or mold, and the method of compaction also influences the combustion of the product.

Compaction pressure

The pressure applied during compaction is crucial to obtaining dense, strong charcoal. The optimum pressure is generally between 5 and 10 MPa to ensure charcoal strength while avoiding excessive deformation. Insufficient pressure results in brittle charcoals, while too much pressure can compromise the internal structure.

Compaction speed

The speed at which pressure is applied plays a part in the consistency of the final product. Too fast a compaction speed can lead to internal cracks, while too slow a speed could affect productivity.

Drying

Drying removes moisture and ensures optimum combustion. The final moisture content of briquettes should be less than 10% to minimize smoke and improve calorific value. Certain factors can also influence the drying process. For example, high humidity can slow down the drying process, thereby increasing the drying time. Residual moisture has a direct influence on calorific value, as poorly dried briquettes will have incomplete combustion, resulting in the production of additional gases, including carbon monoxide, a chemical agent that is dangerous to health, and the carbon responsible for the black colour of smoke. For consistent results, the use of temperature-controlled dryers is recommended.

RESULTS

The results of the study demonstrate the positive impact of the production of ecological paving stones and green charcoal in the context of rapid urbanization. The use of eco-friendly paving stones makes a significant contribution to reducing CO_2 emissions by replacing traditional building materials and reducing reliance on carbon-intensive products [4,7,8,25,39]. In addition, the incorporation of green charcoal, derived from organic waste, present am alternative for clean energy (SDG7), and reduces the pressure on forest resources, leading to a significant reduction in deforestation [8,9,13,18,24,35].

The physico-mechanical tests on ecological paving stones showed an average compressive strength of 30 MPa, comparable to standard concrete paving stones (25 to 35 MPa). The PCA shows that compressive strength accounts for 45% of the total variance in mechanical performance. Abrasion tests reveal a 5% loss of mass after 500 cycles, while wear resistance, combined with compressive strength, explains 30% of the variance, confirming the durability of the pavers. The water absorption rate of the pavers, evaluated at 6%, is lower than that of traditional concrete pavers, generally around 8 to 10%, which contributes to 25% of the variance, underlining the importance of porosity in the durability of pavers in a damp environment.

In terms of environmental impact, green charcoal reduces CO_2 emissions by 20% on average compared with traditional charcoal, accounting for 35% of the variance in environmental impact. Green charcoal production also results in an estimated 15% average reduction in deforestation, with this variable explaining 40% of the observed variance.

The Role of Ecological Paving Stones in Sustainable Urban Development

Ecological paving stones integrate sustainability into urban development by promoting sustainable infrastructure, environmental resilience, and facilitating efficient waste management. It represents a great alternative for the conventional paving stone and one of the pathways to achieve the SDG9. These materials, manufactured from recycled and local resources, not only reduce the carbon footprint associated with traditional paving methods but also serve as effective permeable surfaces that filter stormwater, mitigating urban runoff and flooding. The installation of ecological paving stones can transform cities into greener environments.

Green Coal: An Innovative Approach to Sustainable Energy

The development of Green Coal represents a transformative advancement in sustainable energy solutions, particularly when integrated with urban sustainability initiatives. As cities face escalating energy demands and environmental degradation, alternative energy like green charcoal derived from organic waste and biomass offer a dual benefit of reducing carbon emissions and addressing waste management challenges. By leveraging local waste materials, the production of green charcoal not only minimizes the utilization on fossil fuels in the local community but also enhances the circular economy by valorizing construction and demolition waste (C&DW) within urban settings. Furthermore, this innovation aligns with global efforts to transition towards more sustainable construction practices [1,2].

Benefits and Challenges of Implementing Local Production Systems

The implementation of local production systems for ecological paving stones and green coal presents significant direct and indirect benefits alongside notable challenges. This specific context approaches not only lead directly to sustainable urbanization, but also promote economic growth by generating jobs and supporting local businesses and reduce urban pollution associated with building materials and waste indirectly. Moreover, the utilization of local resources can enhance community resilience, fostering a connection between inhabitants and the environment. However, challenges include potential initial costs and the necessity for investment in technology and training to ensure quality and efficiency in production (Tab 1). Furthermore, as highlight in the table 1 transitioning from traditional production methods may face

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resistance from established industry players and require comprehensive policy frameworks to incentivize sustainable practices within local economies [52].

Table 1 : Benefits-challenges of local production

Benefits	**Challenges**
Support for Local Economy	Limited Technical Expertise
Minimized Carbon Footprint	Regulatory Hurdles
Enhanced Community Engagement	Market Competition
Increased Job Creation	Sustainability of Production
Improved Waste Management	Access to Resources

DISCUSSION OF THE RESULTS

The results show that ecological pavers not only reduce CO_2 emissions, but also offer strong mechanical performance and significant environmental benefits. The compressive strength of eco-friendly pavers, which is comparable to that of standard concrete pavers, demonstrates their potential for urban infrastructure. The identification of compressive strength as contributing to 45% of the total variance in mechanical performance underlines its crucial role in the design of sustainable materials. The observed variability in mechanical properties could be related to differences in material composition, manufacturing processes and curing conditions.

The low loss of mass in wear tests (5%) confirms that ecological pavers are suitable for urban environments where wear is a determining factor. In addition, the low water absorption rate (6%) reinforces their durability in damp environments, reducing the risks associated with freeze-thaw cycles. The limited porosity of the pavers, contributing 25% of the total variance, shows the importance of controlling this property to improve long-term resistance.

The environmental impact of burning green coal, with an average 20% reduction in CO_2 emissions, shows that sustainable practices can significantly reduce the carbon footprint. The average 15% reduction in local deforestation also highlights the effectiveness of this approach to managing forest resources.

CONCLUSION

The adoption of circular economy principles in urban practices via the local production of ecological paving stone and green charcoal, as demonstrated in this study, shows that recycling and reuse can effectively transform the carbon-intensive nature of rapid urbanization into a more sustainable model based on eco-friendly materials. In the urban setting, ecological paving stones provide a sustainable alternative to traditional materials, demonstrating strong mechanical performance and durability while reducing landfill waste. Additionally, green charcoal, derived from organic waste is an emergent source of sustainable energy, reducing carbon emissions and helping to curb deforestation. By promoting recycling, reuse, and energy production, this integrated approach addresses urban waste and CO_2 emissions. It supports sustainable construction (SDG9) and clean energy (SDG7), fostering economic development (SDG8) while preserving natural resources for future generations. The findings advocate for a strategic shift towards environmentally friendly urban practices to ensure long-term sustainability

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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