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A Sustainable Approach: Biochar and its Potential Use in Agriculture

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ABSTRACT

There are about 15 billion tons of carbonaceous waste produced worldwide each year. If this waste could be used efficiently to generate energy and provide long-lasting environmental benefits, it could make a major contribution to global development. Biomass pyrolysis is an emerging renewable energy and material conversion technology that can produce carbon-based biochar and syngas (a mixture of carbon monoxide and hydrogen) for fuel and environmental benefits. Since biochar can be stored in the ground, this renewable energy and material conversion technology is sustainable and it also has the potential to increase crop production by enhancing the ability of plants to extract nutrients from the soil. Biochar produced from waste biomass may also decrease the negative effects of agricultural land use on the water cycle. This document reports on the status of biochar research with details of the environmental and economic benefits associated with biochar production and also summarizes the potential and opportunities for biochar use in agriculture.

Key words: Agriculture, Biochar, Climate change, Pyrolysis.

Although much progress has been made in the treatment of waste and the development of recycling technologies, there is an increasing problem with the disposal of large quantities of untreated waste. Waste streams include waste material from mining, industrial processing, waste generated from the oil and gas industry and various other sources. In many cases, some types of waste have no economic value. This has led to a situation where the waste is stored in landfills, which creates problems of environmental contamination and pollution. Also, most landfills lack adequate technology to prevent leachate from migrating into the environment, which results in the loss of potentially valuable resources (*e.g.* water, gas, nutrients). Landfills are also an expensive method of waste management. In comparison, pyrolysis offers a potential alternative to landfills (Zaman *et al.,* 2017).

Efficient use of huge amount of biomasses, available as crop and agro forestry residues and other farm wastes by converting it in to a useful source of soil amendment. In this concern, biochar is an organic soil amendment, has emerged as a potential strategy to mitigate climate change, to maintain soil health and ensure the sustainable food production at the global scale (Ramamoorthy *et al.,* 2024). Pyrolysis is a process where waste is broken down at high temperatures into a gas and a char product which can be collected. The end products are energy materials which can then be sold to the customer. Pyrolysis is a relatively simple technology to use and requires a little operating cost (Czajczyńska *et al.,* 2017). The energy required is directly related to the mass of feedstock; the greater the mass, the greater the cost of energy input. The products of pyrolysis, *i.e.*, the gaseous products and the char product are recyclable. The gaseous products are often used directly as fuel. The char product can be used for land-filling or used as a mulch or soil amendment to supply nutrients and also help to improve the condition of the soil. The product also offers environmental benefits; by removing the contaminants from the air, carbon dioxide emissions are reduced and since the gas is an inert material, it will not contaminate the air (Singh *et al.,* 2022).

Biomass is used as a fuel and a raw material in the production of chemicals and energy. The amount of biomass produced annually worldwide is about 15 billion tons and is increasing annually. Approximately 45% of this biomass is used as fuel for power generation. The remaining 55% is converted to a variety of chemicals and fuels used to make things like plastics, cosmetics, detergents, pesticides and other types of consumer products. The amount of biomass used for these purposes in 2010 was about 8.2 billion tons (Irmak, 2017). To provide enough biomass to meet the global demand, a sustainable strategy must be developed to ensure that current biomass

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use does not overburden the environment or deplete resources that would be available for future generations.

One promising area of research to increase the efficiency and sustainability of biomass utilization is in the production of carbon-rich compounds such as biochar and syngas (a mixture of carbon monoxide and hydrogen). Biochar is a porous material composed of more than 60% carbon that can be produced from a wide variety of biomass resources. It has many potential uses including soil amendment, bio-augmentation and reducing soil erosion (Rawat *et al.,* 2019). However, more research is needed to determine the best strategy for its use. For the full environmental and economic benefits of biochar to be realized, additional research is needed on its use, potential methods to produce biochar and how to efficiently and economically use biochar. Syngas has been the focus of considerable research since the 1960s. Syngas is an ideal fuel because it is clean, non-toxic and renewable. Syngas can also be used to make chemicals, plastics and other useful products. A recent development is the use of solid oxide fuel cells to convert syngas into electricity. An important potential use of this technology is in the production of clean energy for transportation and other areas of power generation.

Biochar is the generic name for a class of solid carbon-rich materials produced by high-temperature (400-800°C) pyrolysis of any biomass feedstock at the end of its natural service life cycle (Panwar *et al.,* 2019). The biochar produced is stabilized and has good carbon (C) content and thermal conductivity. This stable form of carbon, which is insoluble in water, is referred to as a char and, more specifically, biochar (C) char or carbon char. The char is formed during the char formation process as a result of the conversion and stabilization of organic feedstock such as agricultural waste, straw, wood, agricultural residue *etc.* Biochar consists of carbon (C) and other elements like hydrogen, oxygen, sodium, magnesium, phosphorus, nitrogen, sulfur, copper and potassium. The most common raw material for producing biochar is wood waste, since the amount of wood waste can be large, the production of biochar is an economical way to produce biogas for the energy needs of society and also to create a way to improve the soil quality, since biochar has the ability to bind the soil together and make the soil more water absorbable. Other useful types of biomass that can be used to create biochar are: food waste, leaves, grass, weeds and agricultural waste.

Chemical composition of biochar

Biochar is created when biomass is combusted in a low-oxygen atmosphere with high temperatures for a period of time. The resultant product is a stable, porous, non-combustible charcoal-like solid residue. The term biochar was first used in the scientific literature in 2005, by Stephen McEwan in his research paper at the University of California, Davis. It is defined as char that is formed the by carbonization of wood, straw, agricultural wastes, or any organic matter under a limited oxygen environment at high temperatures.

The five different compounds found in the biochar, are: Aliphatic carbons (C_1-C_{50}), which are chains of carbon, with one to fifty carbon atoms, Aromatic carbons (C_{50}-C_{50}), aromatic chains with 50 carbon atoms, Oxygenated (C_{50}-C_{50}), oxygen-containing chains with 50 carbon atoms, Hydrogenated (C_{50}-C_{50}), Hydrogen-containing chains with 50 carbon atoms and Water (C_{50}-H_{50}).

Aliphatic carbons (C_1-C_{50})

The aliphatic consists (C_1-C_{50}) consist of non-oxygenated hydrocarbons. The carbon range that begins at the carbon atom with the lowest valency is considered the most reactive, which is the carbon atom C_1. This carbon atom is the starting material for this compound since it is found in almost all forms of life and exists in organic compounds.

Aromatic carbons (C_{50}-C_{50})

The aromatic carbon (C_{50}-C_{50}) compound is the next compound found in biochar. This compound has an aromatic structure that includes at least two carbons that are adjacent to one another and can share one or more electrons. This carbon in biochar because of the highest reactivity can share the largest amount of electrons with other electrons. This carbon is used in the metabolism and energy conversion process of all living organisms and it is the starting material for the creation of the aromatic structure. Aromatic molecules and structures have an aromatic ring or structure, such as benzene, phenol, cinnamic acid, quinoline, pyrene and phenanthrene. The aliphatic ring is usually found in the most simple organic compounds such as ethanol, ethylenediamine, or propane.

Oxygenated

The oxygenated compound is the third compound found in biochar. The oxygen is added to the carbon compound and the oxygenated compound can be found in compounds such as methane, carbon monoxide, ethylene, methyl tert-butyl ether (MTBE) and acetic acid. This compound is present in biochar because it has oxygen atoms added to the carbon chain and it was used as a starting material in the formation of the oxygenated compound.

Hydrogenated

The hydrogenated compound is the fourth compound found in biochar. It consists of hydrogen atoms that are added to the carbon atom, forming a structure with a bond between the carbon and the hydrogen atom. The hydrogenated compound is mostly found in the gas molecules and when it is created by the reaction, it comes from a compound that contains two or more carbon atoms with the number of hydrogen atoms.

Water (C_{50}-H_{50})

The water (C_{50}-H_{50}) compound is the last compound found in biochar. This compound is created when the biochar is subjected to steam treatment to form gas. The water

molecule is not found in the biochar itself, but it is a byproduct and it can have different compounds bound to it, but the primary compound is water.

Other compounds present as traces or as byproducts in biochar are not considered major components. These compounds are ammonia, chlorine, phosphorus, sulfur, calcium, iron, nitrogen, sodium, potassium, magnesium, zinc, copper, lead and vanadium.

Biochar produced from wood

The production process is based on the pyrolysis of solid biomass and involves heating it to between 500°C to 1200°C in an oxygen-poor atmosphere (Guda *et al.,* 2015). During pyrolysis, a fraction of the organic content is decomposed into a mixture of volatile organic compounds (VOCs), including water, carbon monoxide and carbon dioxide. A byproduct of this pyrolysis process is the formation of a charred material called biochar, which may be left on the heated biomass. The charcoal remains after the volatile components have been removed.

Wood-based biochars are usually called activated charcoal because they have been treated to increase their surface area. Different forms of activated charcoal can have impact on their subsequent use. In most cases, wood-based biochars are a dark grey-brown coloured material with a specific surface area (as per ASTM D-2863 or another accepted test) on the order of 400 to 1300 m^2/g. While they are usually produced using the batch pyrolysis process described above, they can also be made using other methods. An Italian company, for example, is using an in-situ approach, in which they are developing a pyrolysis unit inside their plant (Sikarwar *et al.,* 2017). This is a very promising method as it has the advantage of reducing and, in some cases, even eliminating the risk of emissions from outside the plant. To obtain a more uniform material, most wood-based biochar producers heat the raw material to high temperatures in an oxygen-poor atmosphere in a special kiln. The resulting biochar will have a more uniform surface and a higher density.

Plant-based biochars

Today, biochar production is used to increase productivity in the cattle feed industry. While it has become widely used in cattle feed yards in the USA, many other countries around the world have also adopted biochar for bedding material in livestock feed yards (Fig 1). The production process varies depending on the raw material used. The most common method is the production of biochar from straw or corn stover by mixing them with coal tar-liquor or other additives and heating them to temperatures of more than 400°C (Sakhiya *et al.,* 2020). An alternative production process that is used in conjunction with a continuous thermophilic pyrolysis plant is to dry the raw material before pyrolysis. Other raw materials that have been used in the production process are grasses, sawdust, wheat, sunflower, corn and rice husks and rice and soybean. The resulting biochar can be made in many different shapes or forms, depending on the raw material used. The biochar produced can be in the form of pellets, cubes, briquettes and granules, or the form of particles in general. The properties of biochar vary depending on the raw material used and the process used in the production. Biochar can affect water retention capacity, retention of nutrients, retention of trace elements, retention of microorganisms and the release of trace elements (Zhang *et al.,* 2021).

Production of biochar

Biochar is produced from different types of biomasses. The most common materials used to produce biochar are plant residues and agricultural residues. Agricultural residues are normally agricultural by-products that remain after the normal farming activities. Crop residues are straw and leaves of crop plants. The two main production technologies for biochar production are:

1) Slow pyrolysis.
2) Fast pyrolysis.

Slow pyrolysis

Slow pyrolysis is the pyrolysis of biomass in an oxygen-free atmosphere at temperatures between 300°C and 500°C (Table 1). The process is operated for about 2-6 hours, during which the biomass is mixed with coke or coal dust and heated (Rashidi and Yusup, 2020). The product of slow pyrolysis is a black material called biochar, which consists of non-condensable gases, volatiles, condensable gaseous compounds and bio-char. The production of biochar using slow pyrolysis is energy-intensive. It requires the use of heat for production. Moreover, it is a slow process that requires many hours to complete.

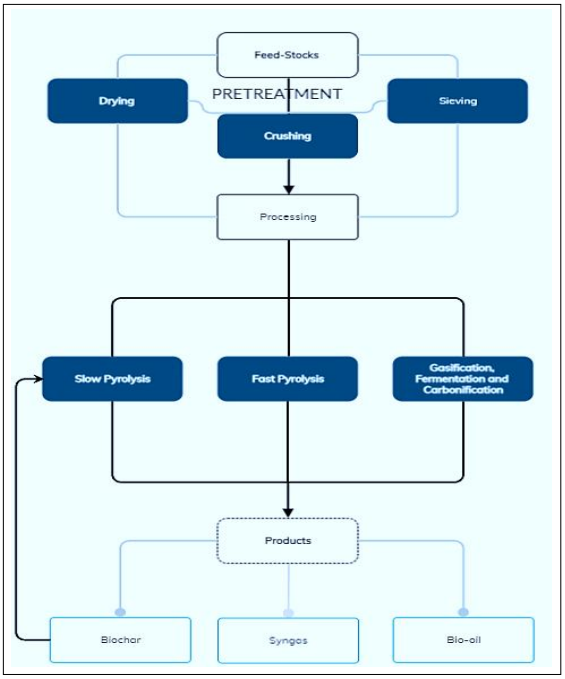


Fig 1: Process of production of biochar.

The production of biochar by slow pyrolysis has the following advantages:

1) Produces a lot of non-condensable gases.
2) Reduces the demand for coal.
3) Reduces the volume of smog.
4) Uses biomass waste materials that can be available on the local farms.

Fast pyrolysis

Fast pyrolysis is the pyrolysis of biomass in a short period (10 to 30 minutes). A typical fast pyrolysis reactor consists of a reactor. The reactor has a pyrolysis chamber. The pyrolysis chamber has a lid that closes the reactor. The lid of the pyrolysis chamber is made of perforated stainless steel or ceramic. Gas with a temperature of over 700°C is blown into the pyrolysis chamber to generate pyrolysis heat (Table 1). This generates a lot of heat during the process. This heat is then transferred to the biomass by the perforated lid. The biomass in the pyrolysis chamber is quickly heated to above 600°C (Rashidi and Yusup, 2020). The heating process takes place in just 10 to 30 minutes. The heating process is stopped when the biomass temperature reaches 400°C. Typical biomass is sawdust.

Fast pyrolysis can be classified into high-temperature pyrolysis and low-temperature pyrolysis. In high-temperature pyrolysis, the pyrolysis chamber is heated to over 800°C. Gas is blown into the pyrolysis chamber at temperatures exceeding 800°C to quickly generate heat and to raise the pyrolysis temperature. The pyrolysis temperature is then maintained at temperatures above 600°C. In low-temperature pyrolysis, the pyrolysis chamber is heated to below 200°C. Gas is blown into the pyrolysis chamber at temperatures below 200°C. The pyrolysis chamber is sealed to generate the required heat (Rashidi and Yusup, 2020). During the heating process in both types of fast pyrolysis, the temperature in the pyrolysis chamber is controlled to prevent the reactor from overheating. Some reactors can achieve the required heating by using a combination of radiant heat and conductive heat (Fig 2).

Biochar production can be either batch or continuous. In a continuous process, a reactor system is designed that provides a constant stream of material through the reactor. Biochar production in continuous reactors reduces the risks of emissions. The continuous process can also be performed in fixed or mobile plant systems. One of the best-known continuous pyrolysis processes is the tubular reactor technology developed by CAST (Canadian Agricultural Services and Technologies) in 1991. The reactor tube is heated by a flow of hot oil, usually a diesel engine, through the centre of the tube. The outside of the tube is covered with a metal grate. This is removed after the production process is completed and the reactor cooled (Fig 2).

Continuous biochar production

Continuous biochar production has developed over the last decades. Initially developed for the pyrolysis of straw and wood in the 1990s, continuous biochar production was further developed in the 2000s. Continuous processes have the potential to replace batch production systems. There are several continuous pyrolysis and gasification plants in operation or under construction in North America, Europe and Asia.

Several factors make it difficult to compare the production of biochar in different continuous reactors. The

Table 1: Conditions for slow and fast pyrolysis.

Conditions	Slow pyrolysis	Fast pyrolysis
Temperature (°C)	300-700	550-1000
Heating rate (°C/sec)	0.1-1	10-200
Vapour residence time (sec)	450-550	0.5-10
Particle size (mm)	5-50	<1

(Source: A mini-review of biochar synthesis, characterization and related standardization and legislation by Rashidi and Yusup, 2020).

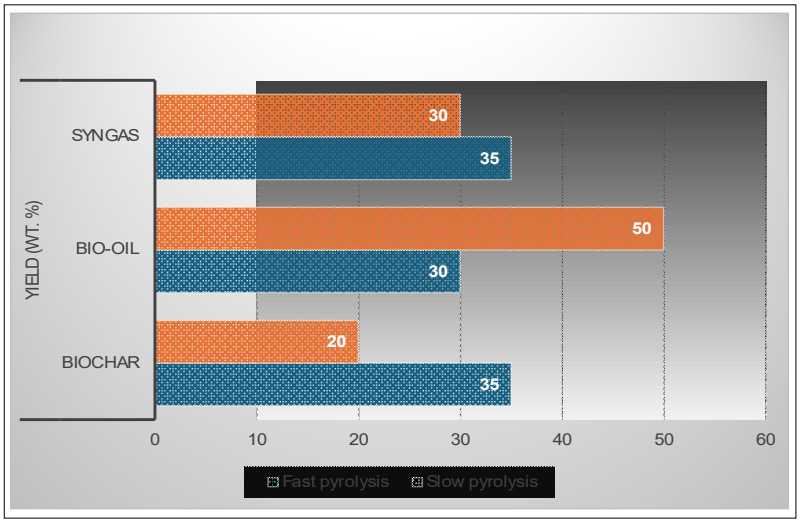


Fig 2: Yield output under different pyrolysis condition.

first and most important factor is the production capacity of the reactor. While there are no common criteria for biochar quality, some authors state that a production capacity of more than 1 ton per hour per litre reactor volume is needed to produce biochar of the quality of good quality activated carbon. It has been shown that the composition of the feed material can also have a significant effect on the final biochar.

Batch processes

The batch process is an ancient technology used since the first domestication of plants. Batch processes are not used for biochar production because they do not involve the addition of materials such as organic materials, which is the key step in biochar production. They are based on the addition of nutrients to soils with a subsequent period of vegetation.

Biochar impact on crop productivity

The studies have proven that a small amount of biochar will greatly increase crop productivity. A study by Qiao-Hong *et al.,* (2014) concluded that biochar has a higher effect on maize plants than any other plant because maize requires the most nitrogen. One study showed that adding biochar to the soil led to an increase in plant biomass, especially in crop species that are high in nitrogen demand (Rawat *et al.,* 2019).

Horák *et al.* (2020) compared the benefits of biochar in three crops and concluded that there were more benefits in corn than in other crops and the most benefits were observed when both biochar and chemical fertilizer were applied to the soil. Biochar has been shown to promote plant growth by increasing soil fertility. Biochar can increase phosphorus availability in the soil and the growth of root tissue. It can also increase the soil's nitrogen retention capacity, making more of the available nitrogen available to the crops. However, Rawat *et al.* (2019) found that biochar caused a detrimental effect on plant growth when grown in medium containing low levels of phosphorus. It was found that biochar reduced the absorption of phosphorus in the soil, although it made phosphorus more available in the medium. This study concluded that if biochar was added to soil that is low in phosphorus, it may decrease the plant's growth rate and it may reduce soil quality.

In other studies where biochar was tested against crops, it was found to increase yield. Ding *et al.* (2016) and Jeffery *et al.* (2015) have also found that biochar can have a significant impact on both soil quality and crop yields and this increase in yield can be observed even in low-yield crop species also.

The mechanisms by which biochar stimulates plant growth are not yet fully understood. Some of the reasons why biochar can have a positive effect on crop growth may be because it acts as an organic fertilizer, it may provide the nitrogen, water and micronutrients needed for plant growth and it may serve as a physical barrier, trapping pests and pathogens in the soil. It may also aid in protecting the plants against temperature extremes and heavy rains (Zhang *et al.,* 2021).

Biochar has also been used to promote the growth of trees. Biochar can improve the conditions of soil used for the growth of trees and it can protect the trees from soil erosion and salt accumulation. Biochar also has the ability to absorb gases, such as carbon dioxide and methane and can serve as a carbon sink. Biochar's application has the potential to change the carbon cycle and reduce the levels of carbon dioxide and methane in the atmosphere. Lefebvre *et al.* (2019) conducted a study in the tropics and showed that planting a tree with biochar is more effective than plant without biochar. The added benefits were the reduction of carbon dioxide and methane, soil quality improvement and enhanced biodiversity. One study found that in a tropical environment, adding 10% biochar to the soil enhanced the growth of trees, shrubs and other vegetation, as well as increasing the amount of soil nutrients. Studies in subtropical conditions reported that the soil was slightly depleted in nitrogen and phosphorus, yet it showed some positive impacts of adding biochar to the soil. Another study tested biochar in tropical conditions in order to compare the effects of biochar on the growth of pine trees, cocoa and coffee and found that biochar added to the soil with these trees yielded a greater increase in tree growth compared to control soils. It was also found that the biochar increased nitrogen and phosphorus retention in the soil and improved the soil pH, even though the soil became slightly depleted in these nutrients (Zhang *et al.,* 2021).

Biochar's impact on crop performance varies with soil type. One study concluded that the use of biochar was an effective and long-term method to improve the soil quality of agricultural land. However, in the study in the medium to high phosphorus levels soils in the tropics found that biochar is effective in improving the growth of trees and producing cocoa and coffee, regardless of soil phosphorus content.

Biochar for climate change mitigation

Biochar, one of the most promising technologies to mitigate climate change, is a black, non-combustible substance produced by the pyrolysis of organic material such as wood, straw, crop residues and grass, which, after a long period of storage, reduces soil carbon levels and can increase carbon sequestration capacity. This is because biochar stabilizes and binds to organic and inorganic soil particles, which facilitates the decomposition of carbon, thus mitigating emissions from human activities (Lehmann *et al.,* 2021). Biochar is a porous, water-stable form of charcoal that is stable under aerobic and anaerobic conditions. The product may be applied on top of the soil, for example in orchards, agricultural fields and urban gardens to mitigate the emissions from organic manure and green waste that are applied as fertilizers. The use of biochar in agriculture for food production as a sustainable alternative to fertilizers has become a popular and rapidly growing practice in many countries around the world. In this context, organic waste such as manure, straw and crop residues are the main sources of biochar production.

While the climate change mitigation potential of biochar was assessed in the first decade of the 21st century, there has been an accelerated expansion of this technology as a result of new scientific evidence and, in particular, increasing public awareness and concern. In the United Kingdom, Europe and the United States, biochar is a topic of significant importance and attention. This is most likely due to many initiatives that have been developed or initiated in these countries to study, implement and/or exploit the potential benefits of this practice (Paliwal, 2020).

The global environmental effects of climate change, which can result in catastrophic events such as extreme weather events, the degradation of ecosystems and increased disease prevalence, are of great concern for the planet. Among the solutions that may be put into practice to mitigate the effects of climate change are the reduction of carbon emissions, the enhancement of carbon sequestration and the use of soils as carbon sinks. Biochar may be an excellent solution in that it has high carbon sequestration potential and, if stored in a long-term stable form, is capable of providing a carbon sink shortly, as evidenced by the findings of the IPCC (2014). These qualities give biochar huge potential for both climate mitigation and food production.

Biochar is an organic-carbon-rich material with very high carbon content and a structure rich in oxygen functional groups. The high organic content makes biochar a highly porous material and ensures a high level of water stability. Biochar is applied as an amendment to the soil to increase its carbon storage capacity and, at the same time, create a favourable environment for soil microorganisms (Das *et al.,* 2021). Therefore, biochar has the potential to significantly slow the emission of greenhouse gases, which result from natural processes, anthropogenic activities such as land clearing and fertilization and through transport and combustion of fossil fuels. This potential makes biochar a "win-win" solution to mitigate climate change by increasing the amount of carbon sequestered in the soil and thus potentially acting as a carbon sink (Srinivasarao *et al.,* 2013).

CONCLUSION

Agriculture is a dynamic industry that has been changing rapidly over the last decade. Increasing concerns about the environment have led to a strong focus on reducing or eliminating greenhouse gas emissions. A major concern for most farmers is the lack of potentially profitable options for reducing or eliminating their greenhouse gas emissions. In addition, there is growing recognition that agriculture must meet the growing needs of a demanding, growing population while remaining a sustainable and sustainable food production system. As a result, many farmers are turning to alternative energy and bioenergy, to reduce their greenhouse gas emissions and are now looking for solutions to improve the soil to prevent erosion and increase the availability of water and nutrients. To make the soil more sustainable and to increase the fertility of the soil, some researchers are looking at the use of biochar. Biochar, or charcoal, is a solid carbon compound that is formed from the carbon in plant matter during decomposition. The production and use of biochar is a simple and environmentally friendly approach to increase the sustainability of soil and water resources and may provide an option for reducing soil erosion and increasing soil carbon content.

Conflict of interest

All authors declared that there is no conflict of interest at all.

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