Chapter 3
Biochar for Improving Crop Productivity and Soil Fertility

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Abstract Biochar application to soils can both sequester carbon in the long term, and improve soil fertility by storing nutrients and water. Biochar is produced by pyrolysis of biomass and biomass residues at high temperature. Here we review biochar application to soil with focus on improving crop productivity and soil fertility. The effect of biochar are highly variable depending on the type of biochar and the experimental conditions. Biochar modify significantly soil properties.

Keywords Biochar · Temperature · Plants · Climate change

3.1 Introduction

Soil is a medium for plant growth and provide support, minerals and water to the plant for survival. Various factors such as environment, soil condition, cultural/management operations and fertilizer application affect plants growth and development (Reis et al. 2016). The use of nitrogen-based fertilizers can't be ignored because of disfavor, but

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it's fabulous for the worldwide global aggregation but its excessive use can contaminate the environment through leaching, runoff and volatilization of the nutrient (Serra gas emission) (Norse and Xiaotang 2015). Therefore, the use of biochar in low-fertility soils is a useful technique for improve soil carbon, soil health its crop productivity (Van Zwieten et al. 2010). Biochar is a carbonaceous compost that comes from the thermal decomposition of vegetable residues and organic waste. The application of biochar has generated an ever-increasing interest in the recovery of nutrients from the ground. The use of biochar can improve the growth of the plant by improving the availability of nutrients, enhancing the microbial activity, the capacity to treat and nutrient of the water and increasing the apparent density. The application and management of biochar and climatic factors influence notably the physical-chemical property of the soil due to the slow rate of decomposition and the prolongation of soil fertility (Lima et al. 2002). However, biochar is highly recalcitrant to microbial decomposition and guarantees long-term benefits for soil fertility (Lima et al. 2002).

The integration of biochar with synthetic fertilizers can meliorate the addressable culture (Lima et al. 2002). Because the accumulation of biochar in the soil implies a diverse nitrogen pool, further study is necessary to increase the length of nitrogen restriction and the rate of riling (Kochanek et al. 2016). The biochar can be grown at temperatures below 350 °C or 550 °C with a C:N rate of 43 and 49 and is used in the ratio of 10 g kg^{-1} to its clayey soil. This has favored the mineralization of the more undecomposed fractions probably due to the effect of in scone biochar (Shaheen et al. 2019). The biochar product through the low temperature at the end has increased the pH of the soil and has also increased the exchange of soil microbes (Zhao et al. 2013; Esfandbod et al. 2017).

Climate change is affecting our agriculture sector (Irfan et al. 2021; Wajid et al. 2017; Yang et al. 2017; Zahida et al. 2017; Depeng et al. 2018; Hussain et al. 2020; Shafi et al. 2020; Wahid et al. 2020; Subhan et al. 2020; Zafar-ul-Hye et al. 2020a, b; Zafar et al. 2021; Adnan et al. 2020; Ilyas et al. 2020; Saleem et al. 2020a, b, c; Rehman 2020; Frahat et al. 2020; Wu et al. 2020; Mubeen et al. 2020; Farhana 2020; Wu et al. 2019; Ahmad et al. 2019; Baseer et al. 2019). Biochar can play a vital role in response to climate change because it can improve crop yield, soil microbial activity and decrease nutrients leaching. However, little attention has been given to biochar application in the process of biological N_2 fixation through its application to legume crops.

Potential benefits of applying biochar to agricultural soil include improved soil structure and soil moisture retention, changes in soil pH and micro-nutrient availability, positive effects on soil microorganisms, e.g. increased biological N_2 fixation by rhizobia in legumes and high levels of colonization by mycorrhizal fungi and plant growth promoting organisms in the rhizosphere. Biochar incorporation into agricultural soils not only changes their biology, but is also likely to have a strong correlated effect on their nitrogen dynamics. Since the C/N ratio of biochar is usually relatively high, initial mineralization of its available C would result in nitrogen (N) immobilization in the short term. This has been reported primarily in N-limited tropical soils (reduced N uptake and plant yields). The effects on soil nitrogen dynamics of biochar applications alone or in combination with mineral nitrogen fertilizers have been the focus of few recent studies. These experiments were carried out with the aim of studying the direct effect of biochar on legumes and the residual effects of biochar and legumes along with different nitrogen levels for subsequent crops of maize and wheat in the increase in productivity, in the improvement of soil quality and in the achievement of sustainability in the cultivation system based on cereals (Cao et al. 2010) (Table 3.1).

3.2 Biochar and Crop Productivity

Biochar is one of the efficient soil amendments which are used predominantly for the commercialized crops production. However, the data related to biochar effect on the crop production is limited as compare to his use and composition. Therefore, the

Table 3.1 Plant responses to biochar application

Source of biochar and application rate	Test crop	Crop responses	Reasons of crop response given by author	Reference
Unknown 0.5 t ha^{-1}	Soybean	Biomass increased by 51%	Increased soil water holding capacity and color of soil	
Unknown 5 and 15 t ha-1	Soybean	Yield reduced by 37%	pH induced micro-nutrients deficiency	
Wood biochar	Cereal	Enhances plant growth	Improving soil physical and biological properties	
Bamboo	Tea tree	Height and volume increased by 20 and 40%	Nutrient retention and balance pH	
Bark of acacia 37 t ha^{-1}	Maize and legumes	200% in yield with fertilizer application	Enhance the availability of P and N also reduce nutrient losses	
Wood biochar	Sorghum and rice	Increased yield when biochar applied with fertilizer as compared to biochar alone	Nutrient retention	
Rice husk 10 t ha^{-1}	Maize soybean	10–40% yield increased	Increased pH	
Green waste 0–100 t ha^{-1}	Wheat	Yield increased up to 40%	Improving physical properties of soil	
Wood charcoal	Wheat	–	Reduced N leaching	
Forest wood charcoal	Maize	–	10% lower bulk density	
Biochar created from modern pyrolysis techniques	Legumes	Positive crop responses	Reducing soil acidity and aluminum toxicity	Glaser et al. (2002)

numbers of tests related to soil and field evaluations are required to recommend different mount of biochar to amend the soil for the qualitative and quantitative production of the crop. Due to lack of limited information and research in the current literature, biochar application is a need of the day for getting more information and benefits. Characteristic of a particular biochar depends on the composition of its material, thus application rates if a particular biochar largely relates to the composition matrix. Several scientific evidences depicted a significant effect of biochar on crop yield and overall growth and development while applied at a rate of 5–50 t ha^{-1} along with adequate plant nourishment (Jalal et al. 2020). Biochar application can increase the value of the standing crops (Cao et al. 2010; Jalal et al. 2020). Thus enhance the yield and development of plants. An increased yield (28–40%) in maize crop was observed after 50 t ha^{-1} biochar application in Pakistani climatic condition (Jalal et al. 2020; Oguntunde et al. 2004) along with biochar at the rate of 90 g kg^{-1} to a manimum-fertile tropical soil, this is not only enhances the Nitrogen fixation rate in bean plants (*Phaseolus vulgaris*) from 50% to 72%, it is also have positive effect on the yield and biomass of bean (Oguntunde et al. 2004; Rondon et al. 2007).

Biochar ammendents in Northern Laos region of United States, categorically known for low Phosphorus availability results in higher grian yield of highlands rice (*Oryza sativa*) (Asai et al. 2009; Silber et al. 2010). All these above mentioned soil characteristics are closely interlinked and may act synergistically towards overall improvement crop productivity and efficiency. Numerous research findings justify the efficient use of biochar for crop improvement (Lehmann et al. 2003), however in certain specific agro-climatic zone the positive effect of biochar inadequate, while some scientist reported negative responses (Mikan and Abrams 1995). Several studies conducted in tropical and temperate agro-climatic conditions reported positive crop response to biochar application, increasing plant growth and development, robust microbial activity, enhanced water retention capacity and reduce nutrient leaching issue (Silber et al. 2010).

Application of biochar enhances nitrogen fixation and useful mycorrhizal relationship in beans (*Phaseolus vulgaris*) (Zhang et al. 2010). Research findings exposed that the positive effect of biochar on plant biomass and development of a crop enhances over time after its incorporation into the soil. Biochar can influence the physiochemical properties of soil, thus it has been reported to increase the fresh and dry yield of sesbania and cowpea (Arif et al. 2015). Furthermore, a research study depicted that biochar can enhance the water holding for more time water and soil nutrient preservation, it make sure the availability and optimum uptake of nutrients from the root zone for synthesis of higher photosynthate which can results in high dry matter content (Elmer et al. 2010).

In case of a study on cowpea and sesbania, the fresh and dry yield was recorded high in second year as compare to first year of experimental trial, illustrating the abundant of nutrients discharge both from legumes as well as biochar breakdown after a year (Arif et al. 2015). Grain and biological yield of mung bean significantly improved in the biochar applied experimental plots, attributes to the direct accessibility of nutrients mostly nitrogen all over the growing season from various biochar sources (Gruss et al. 2019), thus contributing to soil and crop productivity. Likewise, combined application of biochar from charcoal sources and organic fertilizers displayed positive plant growth responses suggesting a strong synergistic relationship for plant development (Yoshida et al. 2008). Biochar showed increased grain yield for different crop species in growing areas with minimum phosphorus (P) availability and also improved the reaction to nitrogen (N) and NP fertilizer applications.

Soil moisture, nutrient matrix and various yield traits such as grains ear^{-1} and grain output of corn is predominantly affected by biochar amendments in soil (Marshall et al. 2019). Various yield components contributes to the overall Grain yield. Application of biochar increased the grain and their overall weight level and seed pod^{-1} (Arif et al. 2015). Soil application with biochar amendments enhances yield and all yield related parameters of legume crops (Mikan and Abrams 1995), explaining the optimum influence of biochar is to provide more nutrient to the soil (Hafiz et al. 2018; Tariq et al. 2018; Fahad and Bano 2012; Fahad et al. 2013, 2014a, b, 2015a, b, 2016a, b, c, d, 2017, 2018a, b, 2019a, b, 2020, 2021a, b, c, d, e, f, 2022a, b; Hesham and Fahad 2020. Iqra et al. 2020; Akbar et al. 2020; Mahar et al. 2020; Noor et al. 2020; Bayram et al. 2020; Amanullah 2017, 2018a, b).

Biotic activity of nitrogen fixing organisms improves with application of biochar thus effecting crop total biomass (Joseph et al. 2010). Nutrient leaching rate decreases with providing of Biochar into the soil which enhances the nutrient cycling and therefore creates a positive influence on crop yield and quality. Biochar has the capability to maintain and make available bio-available nutrients for growth of plant uptake in the root zone. For instance, plant can readily utilize the potassium found within biochar composition (Elmer et al. 2010). Biochar creates a varying effect on soil pH and other related chemical properties, depending on the nutrient source and growing situation (Joseph et al. 2010). Moreover, many type of microbes including fungi, nematodes and acidobacteria i.e. mycorrhizae are higher in population in soils amended with biochar (Woolf et al. 2008).

Soil type classified as “Problem Soil”, possessing organic properties such as poor combined stability, high salinity, excessive pH levels (very high or very low) or deficient in nutrients (Paul et al. 2018; Amanullah et al. 2020, 2021; Rashid et al. 2020; Arif et al. 2020; Amir et al. 2020; Saman et al. 2020; Muhammad Tahir et al. 2020; Md Jakirand Allah 2020; Mahmood et al. 2021; Farah et al. 2020; Sadam et al. 2020; Unsar et al. 2020; Fazli et al. 2020; Md. Enamul et al. 2020; Gopakumar et al. 2020; Zia-ur-Rehman 2020; Ayman et al. 2020; Mohammad I. Al-Wabel et al. 2020a, b). This may be successfully rectified and reclaimed by using biochar as an active remedial agent alone or mixed with other organic amendments (Sohi et al. 2010a, b). Sustainable health of soils may rectify with adequate use of biochar (Spokas et al. 2010).

Several studies had reported multiple ways through which biochar can improve the overall soil health and growing condition (Zhang et al. 2018). For instance, enhanced microbial population diversity throughout the soil volume can immensely increase soil fertility and nutrient levels (Ayaz et al. 2021). The protection provided by biochar pores allows microbial populations to multiply and propagates as well increase the nitrogen fixation rate for plant uptake (Paul et al. 2018; Zhang et al. 2020). This phenomena is beneficial for crops mainly non-legumes crop that are not capable to fix their individual nitrogen. In context to plant-soil feeding relationship, it is quite evident and interesting that potassium found in biochar composition is already present in form that is readily available for plat uptake (Senol 2020; Amjad et al. 2020; Ibrar et al. 2020; Sajid et al. 2020; Muhammad et al. 2021; Sidra et al. 2021; Zahir et al. 2021; Sahrish et al. 2022). Also, Biochar is essentially beneficial for crops where nitrogen fixation phenomena is limited or absent (Heitkötter et al. 2015).

Moreover, the amount of carbon in soil enhances and for the short term minimized the pH level in soils, while soils with alkaline activities tends to be most positive for normally grown cash crops such as maize (Dempster et al. 2012). Addition of biochar can improve different soil properties (Haque et al. 2021). While analyze the soil physicochemical characteristic, it was recorded that the application of biochar had improved nitrogen levels as compare toward only fertilizer treatments (1.16% vs. 0.15% soil nitrogen).increasing of biomass up to 9–18%, it was observed that there were high levels of nitrogen within biomass leaves. Utlizing carbon in its solid form also allows soil to improve its nutrient availability and retention (Haque et al. 2021). Type of soil which are subjected to natural weathering due to any possible reason can't retain the nutrients and mineral available in the soil and thus recorded with low Cation Exchange Capacity (CEC) (Haque et al. 2021). It also has positive relationship of increasing water holding capacity but on surface bonding that occurs with enhanced CEC adds to the nutrient maintenance (Haque et al. 2021).

Furthermore, biochar also hold the capability to openly provide nutrients for plant uptake. For instance, the potassium avaliable in biochar obtained from its creative feed stock is mainly bring into being in forms readily existing for plant uptake (Ameloot et al. 2013). Like illustrated in the Fig. 3.1, the rise and fall of soil pH

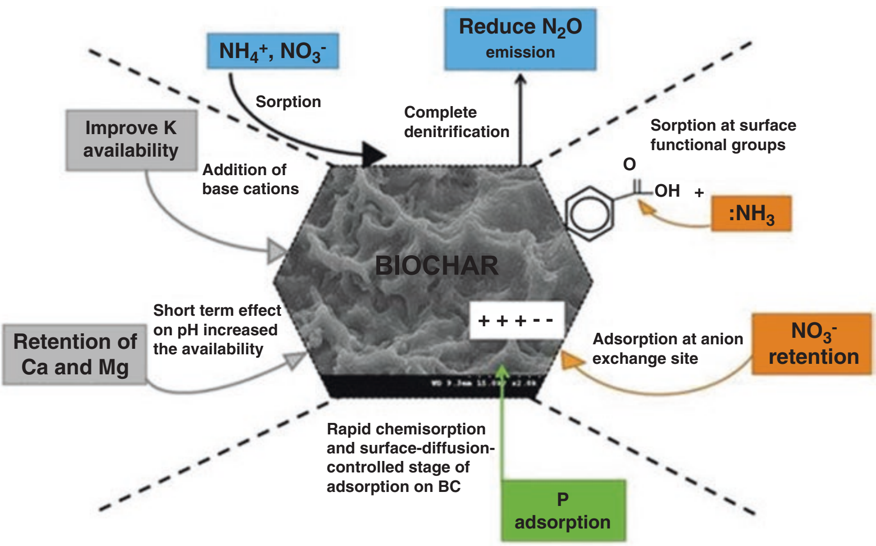

Fig. 3.1 Role of biochar after its application to the soil

after biochar amendments totally depend on the nature, source and characteristics of biochar (Zheng et al. 2013). Generally, bio-chars mixtures formulated from the agricultural residues are likely to be extra alkaline and thus cooperate to enhance soil pH (Borchard et al. 2014; Glaser et al. 2002). Agri- prone biochar compositions have maximum amount of the ash which gives maximum salts quantity to twist more alkaline (Ameloot et al. 2013). Contrary, biochars compositions sourced mainly animal waste product, including bovine manure or chicken litter, are predominantly acidic due to the chemical property they supply to the biochar composite (Yuan et al. 2011).

3.2.1 Biochar as a Soil Amendment

Soil improvement and development is an essential for better quality crop production in most part of the world (Sajjad et al. 2021a, b; Rehana et al. 2021; Yang et al. 2022; Ahmad et al. 2022; Shah et al. 2022; Muhammad et al. 2022; Wiqar et al. 2022; Farhat et al. 2022; Niaz et al. 2022; Ihsan et al. 2022; Chao et al. 2022, Qin et al. 2022; Xue et al. 2022; Ali et al. 2022; Mehmood et al. 2022; El Sabagh et al. 2022; Ibad et al. 2022). Scarcity of basic food elements leading towards meal security is substantially high in sub-Saharan Africa and South Asian regions, recorded for 32% and 22% malnutrition rates in the overall population, respectively (Keske et al. 2020; Deepranjan et al. 2021; Haider et al. 2021; Huang Li et al. 2021; Ikram et al. 2021; Jabborova et al. 2021; Khadim et al. 2021a, b; Manzer et al. 2021; Muzammal et al. 2021; Abdul et al. 2021a, b; Ashfaq et al. 2021; Amjad et al. 2021; Atif et al. 2021; Athar et al. 2021; Adnan et al. 2018a, b, 2019; Akram et al. 2018a, b; Aziz et al. 2017a, b; Chang et al. 2021; Chen et al. 2021; Emre et al. 2021). Even though, the world predominantly work and managed to reduce the malnutrition and famine situation in many countries during the years 1990–1992 and 2001–2003, but countries in Africa, Asia and Latin America are facing this mimic humanitarian disaster.

The historical initiative-"Green Revolution" took by Nobel Laureate Norman Borlaug in 1940s at the International Centre for Maize and Wheat Improvement (CIMMYT), Mexico results in remarkable increase in all sorts of agricultural produce in Asia and Latin American regions. All these advancement in productivity accounts for efficient and improve agricultural practices as well as use of modern technology, including better quality crop varieties, effectual irrigation system and adequate fertilizer and pesticides inputs (Habib et al. 2017; Hafiz et al. 2016, 2019; Ghulam et al. 2021; Guofu et al. 2021; Hafeez et al. 2021; Khan et al. 2021; Kamaran et al. 2017; Muhmmad et al. 2019; Safi et al. 2021; Sajjad et al. 2019; Saud et al. 2013, 2014, 2016, 2017, 2020, 2022a, b; Shah et al. 2013; Qamar et al. 2017; Hamza et al. 2021).

Concept of sustainable soil management and manipulation is presently urged in various applicable forms to implement a 'Doubly inexperienced Revolution' comprising different available conservation technologies (Al-Zahrani et al. 2022; Rajesh et al. 2022; Anam et al. 2021; Deepranjan et al. 2021; Haider et al. 2021; Amjad et al. 2021; Sajjad et al. 2021a, b; Fakhre et al. 2021; Khatun et al. 2021; Ibrar et al. 2021; Bukhari et al. 2021; Haoliang et al. 2022; Sana et al. 2022; Abid et al. 2021; Zaman et al. 2021).

In present day, biochar provides range of opportunities to transform the basic concept of green revolution into a well-developed sustainable agricultural environment. High economical returns even after use of expensive inputs such as fertilizers are closely linked with adequate level of soil organic health and fertility, which can be sustainably maintained by using biochar amendments (Kammann et al. 2016). Biochar is predominantly produced in absence of oxygen via heating of biomass from various sources. Application of biochar can amend physical and chemical properties interacting with soil microbial population, soil matrix and plant root zone interaction with soil (Lehmann et al. 2009). The level of interaction and amendments depicted in a soil types is variable depending on biochar composition nature of biomass, biochar preparation procedure, biochar physical factors and soil environmental properties including soil temperature and moisture's.

Biochar provides immense advantages to any kind of soil, basically working as a soil conditioner refining its physical and organic properties along with enhancement in water conservation capacity and soil nutrient retention (Sohi et al. 2010a, b). Addition of biochar to a soil type depends on various soil properties such as soil ability to produce high quality product, soil nutrient retention, water holding capacity, permanent carbon sequestration, low release of GHG emissions especially nitrous oxide (N_2O) and methane (CH_4) (Kammen et al. 2005; Bracmort et al. 2010; Steiner et al. 2010).

Farmers could be prompted to use biochar on their farms if these blessings can be verified explicitly. In common agricultural practices, the level of carbon degree naturally available in soil can determine the normal regulation of agro-ecosystem and impact the soil fertility and its physical properties majorly soil mixture balance, cation alternate potential and water holding ability (Milne et al. 2007). Ability of soil to provide soil vitamins and nutrients in cation form can be enhanced with biochar application which will ultimately improve plant growth and development. Numerous research studies provide evidences for significant potential of biochar to enhance soil pH levels, decrease lower aluminum toxicity, decline soil tensile capacity, improve the soil conditions for earthworm population and improved efficient fertilizer utility.

Furthermore, several research findings depicts that biochar application and utility can enhance the soil physical properties and grain yield of upland (*Oryza sativa* L.) in region of northern Laos (Spokas et al. 2009). Incorporation biochar can enhance the saturated hydraulic conductivity of upper soil layers and xylem sap glide in rice plant. Predominant soil amendments in form of soil pH improvement, natural carbon and exchangeable cation levels as well as considerable decline in tensile energy (>50 t/ha) can closely linked with biochar utility in different soil types. Biochars improves the cation exchange capability (CEC) for various spoil types especially in case of highly weathered and low nutrient sandy soil, depends on the level of already availability biochar residues and sources f biochar composition.

Application of biochar can also provide various environmental services such as stepped forward soil shape, enhanced microbial pastime and nutrient cycling retention of soil moisture (Sohi et al. 2010a, b). Another significant effect of biochar also well-documented, elaborating the lime effect of biochar often linked with the improved cop yield in tropical acidic soil. Furthermore, application of biochar to alkaline soil But, the addition of biochar to the alkaline soil showed no significant improvement in soil pH and nodultion levels in soil, which is mostly inhibited with use of low soil pH. Though the initial transient flush of labile compounds to the rhizosphere region subsequently followed by use of biochar can improve the nutrient cycling. The yield of legume crops grown in a nutrient poor alkaline soil are observed to get enhance in the second season of the specific crop, suggesting that longer-term advantages of biochar application can improve the crop growth as compare to the primary season. All these applications into the soil for better plant growth and development makes biochar a unique efficient substance, keeping the exchangeable and consequently plant available nutrients in the soil, and supplying the possibility of enhancing crop yields at the same time as reducing environmental pollution via vitamins. Overall, biochar application can be used a modern day concept for improving the soil fertility and higher cop productivity, with environment efficient approach (Ogawa et al. 2009) (Table 3.2).

Furthermore, Black carbon may affect the retention of nutrients and play an important role in extensive range of biogeochemical approaches within the soil, especially for cycling of nutrients (Spokas et al. 2009). Investigated the impact of rate and kind of biochar made from poultry litter under distinctive conditions on the soil exceptional parameters. It was observed that addition of Biochar to the various potting soils resulted in vast special modifications in the chemical and physical properties of soil, inclusive of increase in pH, C, N, and P. It was concluded that specific outcomes of the two Biochars (Produced at 450 °C and 550 °C, respectively) could be associated with their exclusive traits. Drastically, unique modifications in soil biology including microbial biomass and earthworm desire residences were recorded within the two Biochars.

Table 3.2 Effect of biochar on soil properties

Constituent	Consequence	Reference
Cation exchange capacity (CEC)	Increase 50%	Glaser et al. (2002)
Fertilizer use efficiency	Enhance 10–30%	
Liming agent	Enhance pH 0.5–1	
Soil moisture retention	Increase up to 20%	
Crop productivity	Increase 20–120%	
Emission of methane	Enhance 80–100%	
Emission of nitrous oxide	Decrease 40–50%	
Bulk density	Depend on soil	
Biological nitrogen fixation	Increase 30–40%	

3.3 Conclusion

The problem of depletion of agricultural land is due to the pressure caused by the constantly growing population and therefore requires the sustainable exercise of cultivation. It has been suggested that biochar be used as a method to clean up contaminated agricultural soils and improve soil fertility. Additionally, adding biochar to the soil can be one of the best practices to triumph over any biotic stresses in the soil and increase crop productivity. Biochar's high-quality means in soil-plant-water interactions resulted in higher photosynthetic yield and higher nitrogen and water use efficiency. Subsequently, from this comprehensive overview, it could be concluded that biochar has the ability to enhance microbial population and its activities, improve soil habitats, organic nitrogen fixation and plant growth. Therefore, it is recommended to use biochar as a soil amendment for long-term carbon sink healing.

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