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## Impact of Carbon Nanoparticles on Aggregation and Carbon Sequestration under Soil Degradation – a Review

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### ABSTRACT

Soil aggregation, mainly macro- (250–2000  $\mu\text{m}$ ) and micro- (53–250  $\mu\text{m}$ ) aggregates, directly affects the soil system i.e. pore size distribution, the microbial population, soil resistance to erosion, and resistance against degradation. Moreover, macro-aggregates play a significant role in soil organic carbon (SOC) storage and carbon sequestration. However, because macro-aggregates create an environment that facilitates interactions between clay particles and the SOC, protection by macro-aggregates becomes weak. Therefore, the direction of micro-aggregate formation is helpful for long-term soil carbon sequestration. This review suggests that the micro-aggregate protected carbon is promising for assessing the impact of agricultural soil conservation on organic carbon storage in soil. Soil degradation by agriculture practices leads to the destruction of the protective soil aggregate and soil structure. This exposes the labile carbon in these aggregates to microbial interaction. The present review found that SOC change was significantly influenced by organic inputs such as organic nanoparticles (CNPs), especially in sandy and clay soils poor in organic matter.

**Keywords:** Carbon nanoparticles, Aggregation, Soil degradation, Soil organic carbon storage.

### INTRODUCTION

Soil degradation is a serious problem challenging agricultural soil across the globe particularly in the 21<sup>st</sup> century (Dong et al., 2022). Recent data show that in arid and semi-arid areas of the world, degraded soils amount to 3.6 billion ha out of 5.2 billion ha. Soil degradation has numerous types: (i) soil physical degradation, (ii) soil chemical degradation, (iii) soil biological degradation; and (iv) soil ecological degradation (Lal, 2015). Soil physical degradation is the most important physical process that results from decreased structural attributes including pore geometry and continuity, etc. It aggravates a soil's susceptibility to crusting, compaction, decreased water flow, and increased soil desertification. While, chemical degradation results from salinization, acidification, calcium deficiencies, nutrient depletion, and leaching of  $\text{N-NO}_3$  or other essential plant nutrients. Soil biological degradation results from soil organic carbon (SOC) depletion, a decrease in soil carbon sink capacity and a loss in soil biodiversity. The ecological degradation leads to disruption in ecosystem functions for example water flow, and elemental cycling (Lal, 2015; Obalum et al., 2017).

One of the main environmental issues is soil deterioration, which harms soil carbon, nitrogen, potassium, calcium, and magnesium stocks. This affects the soil's overall quality, production, and fertility. SOC is rapidly changed in agricultural soil, particularly under arid and semi-arid conditions, its fractions are extremely sensitive to high temperatures and soil management practices. An increasing body of research indicates that distinct SOC fractions have varied functions and influence soil aggregate formation in different ways (Yousefi et al., 2008). For instance, the carbohydrate (polysaccharide) component of SOM has short-

term effect, whereas humified component has long-lasting effect on soil micro-aggregates stability (Tisdall and Oades 1982). The soil carbon stock is a measure used by the Sustainable Development Goal of the United Nations No. 15.3.1 to assess land degradation. Degradation of the soil can hinder economic growth, especially in some nations where agriculture is usually the primary source of economic growth (Scherr, 2001). The loss of SOC, generally, reduces cation exchange capacity and nutrient availability, which in turn reduces biomass output. This could eventually result in higher soil bulk density (BD), a decline in the stability of soil aggregates, and a drop in organic inputs that lower SOC (Dlamini et al., 2014). Besides, soil aggregation and structure are a key component of soil fertility that affect root dispersion, nutrient and water uptake, soil resistance to erosion and increasing microbial community structure (Mirzaei Aminiyani et al., 2015).

The physical and chemical properties of the soil are changed by increased intensive tillage and agricultural practices, which reduce soil organic matter (SOM), soil permeability, water retention, and soil structural stability by breaking down macro-aggregates into micro-aggregates. As a result, the amount of organic carbon in the soil diminishes and soil erosion is increased. Additionally, it raises pressure, decreases BD and micro-porosity, and generally causes nutrient imbalances. These factors raise the soil's susceptibility to deterioration and have a significant effect on both soil fertility and its capacity to regulate climate change emissions. Thus, the current movement towards sustainable agriculture centers on altering farming methods to lower the need for chemical inputs and tillage, protect biodiversity in the soil, increase soil carbon, and enhance the physical characteristics of the soil (Mechri et al., 2023). It could be concluded that soil quality strongly depends on the degree of

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soil degradation, land use and management practices. Since soil is the most vital natural, non-renewable resource, indexing and predicting its loss/degradation is a key task.

### An overview of the effect of soil organic carbon as a sole indicator of soil degradation

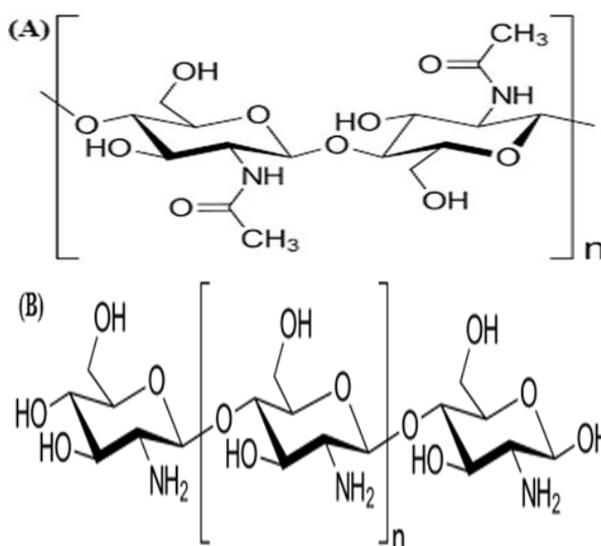
#### Improving soil quality using nanotechnology techniques

Nanotechnology was defined by the National Nanotechnology Initiative as the manipulation of matter with at least one dimension sized from 1 to 100 nanometers (nm). At this scale, commonly known as the nano-scale, surface area and quantum mechanical effects become important in describing properties of matter. The definition of nanotechnology is inclusive of all types of research and technologies that deal with these special properties. It is therefore common to see the plural form "nanotechnologies" as well as "nano-scale technologies" to refer to the broad range of research and applications whose common trait is size (Drexler, 1986).

Nanotechnology is a pioneering technology in numerous fields, including agriculture (Dimetry and Hussein, 2016), because of its special physicochemical characteristics. Nanotechnology-derived materials are used to improve plant growth (Zayed et al., 2017) and as delivery systems to reduce nutrient loss during fertilization, and improve productivity (Adisa et al., 2019). Because biopolymers are abundant, inexpensive, and non-toxic, there has been interest in using them as natural and effective supports (Dohendou et al., 2021). Furthermore, polysaccharide-based entities decorated with nanoparticles have functioned as novel and enhanced (nano) catalysts or sorbents (Nasrollahzadeh et al., 2021). Because they can be loaded with some nutrients, polysaccharide-based entities polymerized with nanomaterials have been used as creative sorbents or more potent (nano) catalysts. They can also be thought of as a source of SOM in the soil and an alternative to conventional fertilization. The remarkable structural properties of natural polysaccharides, which are repeat units of monosaccharides  $[C_n(H_2O)_n]$ , as well as their widespread availability, nontoxicity, flexibility, biocompatibility, and committed potentials have made them into sustainable materials (Nasrollahzadeh et al., 2021). The unique physicochemical properties of the recommended polysaccharides for creating carbon nanoparticles (CNPs) are particularly significant because of their high adsorption capacity, biodegradability, non-toxicity, low cost, and excellent hydrophilicity due to their flexible biopolymer chains with carboxyl (COOH) and hydroxyl (OH) groups that make them well-suited for nutrient attachment (Dohendou et al., 2021) and a source for soil organic carbon (SOC) instead to adding traditional organic matter (OM). There are different types of polysaccharides used for soil protection from degradation and desertification such as chitosan (Olivera et al., 2016; Xu et al., 2019), pectin (Sharma et al., 2016) and Arabic gum (Nasrollahzadeh et al., 2021). Owing to carbon nanoparticles (CNPs) are made entirely of pure polysaccharides via., chitosan, pectin and gum, they are highly stable, environmentally friendly, and low in toxicity. But we currently know very little about how soil reacts to CNPs. Studies on the uses and fate of CNPs in soil are still rare and often only conducted at the laboratory scale. Thus we need to do more research, especially under Egyptian conditions.

### Chitosan compound

Chitosan (CS) is an amino-polysaccharide (Nasrollahzadeh et al., 2021), that consists of N-acetyl-D-glucosamine and D-glucosamine molecules in a linear polymer shape connected by  $\beta$ -(1,4) linkages glycosidic, and it contains hydrophilic functional groups i.e. hydroxyl (OH) and amino ( $NH_2$ ) groups (Zayed et al., 2017). This biopolymer is extracted by a deacetylation process from chitin, a plentiful biopolymer in nature after cellulose. It has been found that CS can adsorb due to the (OH) groups, however, the amine ( $NH_2$ ) groups continue to be the most active group and influence other biopolymer functions (Gibbs et al., 2003). In acidic conditions, CS and its derivatives are cationic characters that promote degradation and allow for ion-exchange interactions or electrostatic attraction with other anionic characters, and their application is considered eco-friendly, low-cost, renewable and sustainable (Nasrollahzadeh et al., 2021). The chemical structure of the chitin and chitosan compounds is shown in Fig. 1.



**Fig. 1. The chemical structure of chitin(A) and chitosan (B) (Gibbs et al., 2003)**

Because of its distinctive physicochemical properties, CS is particularly significant as a biogenic raw material. These properties include (i) abundance and high adsorption capacity and excellent hydrophilicity because it has many (OH) groups; (ii) biopolymer chains' flexible structure, which complements their ability to connect to metal ions; (iii) ease of modification (Dohendou et al., 2021; Nasrollahzadeh et al., 2021). It can increase interparticle cohesion and significantly improve the mechanical properties of sandy soil (Shariatmadari et al., 2020). The matrix of CS serves as a protective stock for loaded agricultural fertilizers, allowing them to be gradually released into the environment (Malerba et al., 2012).

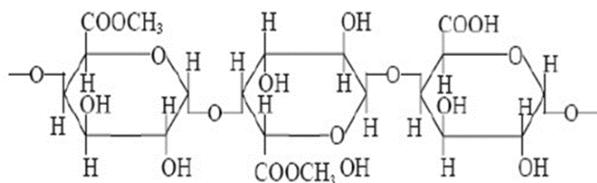
There are many applications for nano-chitosan (NCS) due to its positive surface charge (Malerba and Cerana, 2016), therefore, it is used in nano-fertilization (Khalifa and Hasaneen, 2018), where supplying it with macronutrients to encourage crop development (Abdel-Aziz et al., 2016), and increment the SOC content (Soliman and Mansour, 2024). The foliar spraying with NCS also increases plant growth under conditions of severe water stress, in addition to

increasing the average characteristics of total protein, chlorophyll a, b, proline, carotenoids and soluble sugar (Varamin et al., 2018).

**Pectin compound**

Pectin (PC) is an esterified D-galacturonic acid-based acidic hetero-polysaccharide that exists in  $\alpha$ -(1, 4) linkages of glycosidic (Abdallah et al., 2020), and it is extracted from citrus fruits (Braidwood et al., 2014). This biopolymer, which is a polysaccharide that is widely present in all plant primary cells, is primarily a linear chain consisting of galacturonic acid and a small amount of methyl-esterified carboxyl/hydroxyl groups linked in chains by  $\alpha$ -(1, 4) linkages of glycosidic. Additionally, a small amount of neutral sugars are presented as side chains (Dohendou et al., 2021).

It has a high molecular weight, ranging from 60,000 to 130,000 g mol<sup>-1</sup>, depending on the conditions of its extraction and place of origin. Besides, it is soluble in aqueous and acidic conditions (Abdallah et al., 2020; Braidwood et al., 2014). Also, PC as a biogenic raw material is a particular significance due to its biodegradability, flexibility, low cost, non-toxicity, and freely available (COOH) and (OH) groups because it is an ideal candidate for many agricultural practices (Dohendou et al., 2021). Moreover, Nasrollahzadeh et al., (2021) pointed out that PC is widely known for its adsorption capacities, extremely high active surface and high thermal stability. In addition (Abdallah et al., 2020) mentioned that, PC has physical and chemical adsorption. The chemical structure of pectin is shown in Fig. 2.

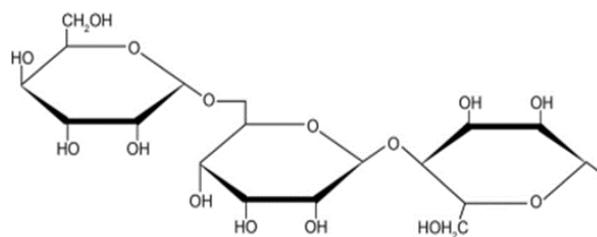


**Fig. 2. The chemical structure of pectin (Abdallah et al., 2020)**

**Arabic gum compound**

Arabic gum (AG) or acacia gum is a hetero polysaccharide; this natural biopolymer is a complex extracted from Acacia trees. It has been employed as an emulsifier, stabilizer, and thickener in the food industry. The components of AG are (1-3)-D galactopyranosyl units, some of which are found in side chains of other carbohydrates including glucuronic acid, arabinose, and rhamnose. These units are found in (1-6) bonds with other carbohydrate contents (Dohendou et al., 2021).

It has been widely used as a thickening agent, dispersing agent, ion exchange resin and binder because of its good ability to change rheological properties; Moreover, it is considered an eco-friendly, green biopolymer (Nasrollahzadeh et al., 2021), it is also used as an additive, a potential stabilizer and certainly a reducing agent in the preparation of various nanocatalysts (Padil et al., 2018), and biosorbent in different applications (Sharma et al., 2018). For these reasons, it can be applied to stabilize nanoparticles. The chemical structure of acacia gum is shown in Fig. 3.

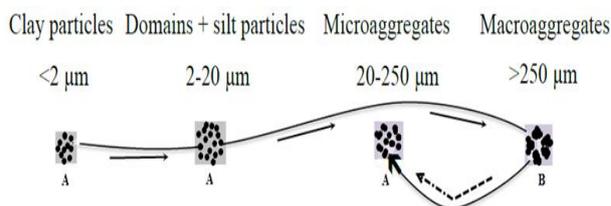


**Fig. 3. The chemical structure of acacia gum (Mariod, 2018)**

**Formation of soil aggregates and their relationship with organic materials**

In addition to providing nutrients, organic matter inputs through organic amendments enhance soil aggregation and promote microbial variety and activity. Particularly in arid and semi-arid areas with poor soil structural stability, where dispersion is typically related to sodicity, the stabilizing of SOM is crucial (D'Odorico et al., 2013). Previous studies proved that the stabilizing effect of organic matter in the soil exceeds the sodium dispersive effect (Ghosh et al., 2010). Organic farming for example has been shown to increase SOC as well as improve soil structural properties like permeability and aggregate stability and reduce runoff by reducing soil erosion (Schweizer et al., 2022). Therefore, soil texture and organic matter are considered the principal abiotic factors that govern the formation and stability of aggregates (Das et al., 2014; Puget, 2000)). Organic inputs that enter the soil cause an increase in soil biomass, which in turn works to increase SOC, which helps improve soil construction and increase the stability of aggregates and soil permeability (Jha et al., 2014).

Sand, particulate organic matter and micro-aggregates are combined to form macro-aggregates, which are then bound by either transitory (fungal hyphae and roots) or transient (produced polysaccharides or added). In contrast, combinations of free primary particles held together by long-lasting binding agents such as organic molecules, calcium and magnesium carbonates, polyvalent cations, and metal oxy (hydro) oxides produce micro-aggregates (Fig.4) (Ghezzehei, 2012; Tisdall and Oades, 1982). The primary water-stable macro-aggregate size was previously demonstrated to be from 0.25 to 1.00 mm (Kercheva et al., 2011), the selection of macro-aggregates was based on their ability to influence soil functioning (Stavi et al., 2011).



**Fig. 4. The chronological formation of aggregates (Tisdall and Oades, 1982) and modified by (Ghezzehei, 2012), A: organic molecules, Ca- and Mg-carbonates, polyvalent cations, and metal oxy (hydro) oxides, B: polysaccharides, roots and fungal hyphae**

The development and stability of macro-aggregates (>250 μm) are mostly attributed to organic binding agents, indicating that organic matter plays a role in aggregate stability (Krol et al., 2013), and (Das et al., 2014) indicated that the application of organic fertilizers for the long-term led

to a significant increase in SOC. This is reflected in the soil's physical properties, especially the aggregates stability. (Wang et al., 2013a) pointed out that long-term application of chemical fertilizers with organic materials can increase the portion of macro-aggregates (>250  $\mu\text{m}$ ) and aggregate stability and reported that applying organic fertilization to the soil achieved a large mean weight diameter (MWD) and high amount of macro-aggregates (>250  $\mu\text{m}$ ). In contrast, it was proven that there was a strong positive correlation between the amount of macro-aggregates (>250  $\mu\text{m}$ ) and MWD (Guber et al., 2005; Wang et al., 2013a). Numerous studies support the link between enhanced aggregate formation and inputs of organic materials (Karami et al., 2012; Williams and Petticrew, 2009).

It is worth noting that, there is a close relationship between the presence of aggregates and the movement of water in the soil and its content from plant-available water. Many studies have shown the importance of adding organic matter to clay loamy or loamy soils that in turn increase the air proportion, as a result of increasing the inter and intra-aggregate spaces. These aggregates are responsible for increasing the pores responsible for transporting and storing water. As the number of meso-pores increases, the processes of drainage, drying, wetting, and the water flow under gravity increase. Thus the pores became hydraulically active (Soliman et al., 2019). The increased organic matter can increase plant available water content, which was explained by greater increases in field capacity compared to wilting point and thus reduced occurrence of water stress (Ankenbauer and Loheide II, 2017; Eden et al., 2017).

Organic carbon is considered the effective component of any organic material, which has a critical effect on the overall stability and structure of the soil (Durigan et al., 2017; Zhou et al., 2020). The sources of SOC are simple organic compounds (polysaccharides), soil organisms (microbial biomass), complex and large humic substances, relatively fresh residue at different stages of decomposition and carbon nanoparticles (CNPs). These substances play an important role as persistent binding agent for formation and stabilization of aggregates (Six et al., 2004). There are some mechanisms for SOC effects on aggregate formation and stability represented in the following points (i) SOC works as a binding factor and is the main component in the aggregates formation (Yousefi et al., 2008; Soliman and Mansour, 2024), (ii) SOC can improve the micro-scale soil internal forces between soil particles which changes the soil surface charge properties and leads to a reduce in the net repulsive force, consequently decreasing the aggregate degradation compared to the state without adding any organic materials (Yu et al., 2017; Yu et al., 2020), (iii) it repels water to decrease wettability of aggregates or increases friction between particles, thereby decreasing the tendency of macro-aggregates to disintegrate in water (Yousefi et al., 2008). Therefore, increasing the SOC content could improve the macro and micro-aggregation and MWD (Das et al., 2014; Guo et al., 2019; Halder et al., 2023). Furthermore, the association of organic carbon with clay could have occurred, thus enhancing soil aggregation and lower bulk density, leading to increased macro-porosity and hydraulic conductivity of the soil (Koop et al., 2023; Soliman and Mansour, 2024).

The stability of organic carbon varies depending on the aggregate sizes. The presence of organic carbon in large aggregates (2-8 mm) has a crucial positive effect on the stability of these aggregates, although the opposite effect was observed for small aggregates <0.25 mm (Das et al., 2014). Also, Jozedaemi and Golchin, 2024 confirmed that the macro-aggregates (>2 mm) contain 47.47 to 57.22% of the total SOC stock. The other factor controlling the formation and stabilization of macro and micro-aggregates in the soil is the type of SOC fractions inside organic materials. One of these fractions is soil polysaccharides from microbial and plant sources which play a vital role in the stabilization of soil micro-aggregates through their structure that allows to bridge the space between soil particles (Yousefi et al., 2008).

#### **Aggregates as a protector of soil organic carbon**

Aggregation has a significant impact on soil carbon cycling. Carbon sequestration depends on soil aggregate stability (Chivenge et al. 2011; Laganietre et al. 2011). Soil aggregates can be divided into two main groups: macro-aggregates (>250  $\mu\text{m}$ ) and micro-aggregates (<250  $\mu\text{m}$ ) according to (Okolo et al., 2020; Tisdall and Oades, 1982). The ability of aggregates to protect and store SOC depends on their size. The protected organic carbon inside macro-aggregates undergoes fast microbial decomposition causing a breakdown of these aggregates (Halder et al., 2022; Lehmann and Kleber, 2015), this leads to formation of small and more stable aggregates with fractions of silt and clay (Halder et al., 2022). Therefore, soil aggregates provide physical protection for SOC by trapping carbon and preventing microbial decomposition (Sekaran et al., 2021; Wang et al., 2019), and stabilization by interaction with metal ions and mineral surfaces (Lützow et al., 2006). Thus, soil macro-aggregates (>2 mm) have an essential role in soil carbon storage compared to micro-aggregates which had little impact (Jozedaemi and Golchin, 2024; Yilmaz et al., 2019).

Several studies proved that SOC in micro-aggregates is less subject to alter than in macro-aggregates which degrades more slowly, so micro-aggregates provide higher physical protection (Igwe and Obalum, 2013; Li et al., 2020; Zhou et al., 2020). The collapse of soil aggregates can enhance the release of protected organic matter due to the low density of most organic materials compared to the other soil components (Maïga-Yaleu et al., 2013; Nie et al., 2015). This loss of protection from macro-aggregates causes the exposure of organic carbon to oxidizing conditions (Lützow et al., 2006). For this reason, the accumulation of organic matter can upgrade soil aggregation, thus protecting SOC from degradation (Wang et al., 2013b). This is consistent with what was indicated by (Wang et al., 2014) observed that SOC mineralization increased by 10 to 80% due to aggregate crushing at the eroded soil.

It could be included that three mechanisms can stabilize the SOC (Six et al., 2002): (i) physically stabilized through micro-aggregation, (ii) close connection with clay and silt particles, (iii) the formation of resistant, biochemically stabilized soil organic matter compounds. Finally, it could be concluded that the formation of soil aggregation is the basis for enhancing the stability of SOC, which can be known as the capacity to increase the residence time of SOC (Berhe and Kleber, 2013; Novara et al., 2012). Thus, high content of SOC can encourage soil aggregation, producing lower runoff rates and reducing soil degradation (Chaplot and Cooper, 2015).

### Soil aggregates and calcium sources

The presence of calcium ( $\text{Ca}^{2+}$ ) in soil enhances the formation of stable micro-aggregates (Six et al., 2004), but adding  $\text{Ca}^{2+}$  with organic matter produce a synergistic effect on soil aggregation which helped in the formation of macro and micro-aggregates, and the impact is more effective after irrigation attributed to the creation of calcium bridges between the clay particles having a negative charge (Yamaguchi et al., 2004).  $\text{Ca}^{2+}$  with organic matter increased the formation of macro-aggregates ( $>2000 \mu\text{m}$ ), the aggregate MWD, and the amount of water-stable aggregates ( $>250 \mu\text{m}$ ) (Vargas et al., 2019; Xie et al., 2023). A significant positive correlation was observed between hydraulic conductivity and soil  $\text{Ca}^{2+}$  content. Hence, the addition of calcium enhanced flocculation, pore stability during wetting and increased hydraulic conductivity (Wuddivira and Camps-Roach, 2007). Calcium cations have a preferential affinity for the carboxyl group in the organic matter, which is essential for creating organometallic bridges capable of consolidating clays. For example, the addition of  $\text{Ca}^{2+}$  cation with liquid humic increases the macro-pores and reduces the bulk density, and this leads to increased aggregation and structural stability of the soil, which in turn can reduce the possibility of erosion (Norambuena et al., 2014).

The addition of nano-calcium helped to decrease the bulk density and increase the stable soil structure. It also helped to increase the hydraulic conductivity of the soil, which helped increase the efficiency of removing sodium from sodic soil. Moreover, it reduces soil electrical conductivity (EC), pH, and the exchangeable sodium percentage (ESP) (Abd El-Halim et al., 2023).

### Carbon nanoparticles and soil aggregates

Nanotechnology could enhance the formation of different aggregate sizes and protect SOC storage in the soil (Soliman and Mansour, 2024). Reducing the size of polymers at the nanoscale can significantly improve the soil physical properties even in the presence of a small amount of it (Givi et al., 2013). These effects may be attributed to their great adhesion, specific surface area, activity and ability to interact with soil colloids (Bayat et al., 2019). Organic nanoparticles (ONPs) are represent a source of natural carbon and highly biodegradable. Therefore, ONPs application can increase enzyme activities, soil microorganisms, and a resultant increase in plant residue decomposition. The conversion of carbon contained in biopolymer is an urgent process during soil carbon cycling (Baldrian et al., 2011).

Application of these compounds encouraged the creation of macro-aggregates, micro-aggregates, MWD (Daraei et al., 2020) and soil hydraulic conductivity (Shariatmadari et al., 2020). For example, applying nano-magnesium oxide helped to increase the total porosity by reducing the density, and increasing the MWD of the aggregate and the saturated hydraulic conductivity (Bayat et al., 2019). The presence of polysaccharides reduces soil disintegration and increases the aggregation process (Carrizo et al., 2015). Furthermore, the application of biopolymers such as chitosan created stabilized soil aggregates (Kannan and Sujatha, 2022; Shariatmadari et al., 2020), erosion control and improvement mechanical properties of sandy soils.

## CONCLUSION

The process of soil aggregation is significant and helps significantly to the enhancement of the physical properties of the soil, including aeration, hydraulic conductivity, and infiltration. Additionally, the aggregation process plays a critical role in improving soil carbon sequestration. This review focuses on the impacts of applying organic materials, especially carbon nanoparticles and organic nano-calcium on mean weight diameter as an index of aggregate stability and organic carbon aggregate size fractions in soil. Nanotechnology techniques could increase the soil organic carbon contents in different size fractions of aggregate and increase carbon sequestration ability in soil.

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## تأثير جسيمات الكربون النانوية على التجمعات وعزل الكربون تحت ظروف تدهور التربة

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### المخلص

يؤثر تجمع التربة، خاصة التجمعات الكبيرة (250-2000 ميكرومتر)، والصغيرة (53-250 ميكرومتر)، بشكل مباشر على نظام التربة، مثل التوزيع الحجمي للمسام، والتجمعات الميكروبية، ومقاومة التربة للتعرية، وتحسين تدهور التربة. علاوة على ذلك، تلعب التجمعات الكبيرة الحجم دوراً مهماً في تخزين الكربون العضوي، وعزله في التربة. ومع ذلك، نظراً لأن التجمعات الكبيرة الحجم تخلق بيئة تسهل التفاعلات بين جزيئات الطين والكربون العضوي بالتربة، فإن الحماية التي توفرها التجمعات الكبيرة للكربون العضوي تصبح ضعيفة. ولذلك، فإن اتجاه تكوين التجمعات الصغيرة مفيد لعزل الكربون في التربة على المدى الطويل. وتشير هذه الدراسة إلى أن حماية الكربون بواسطة التجمعات الصغيرة الحجم يعدّ إعداداً لتقييم تأثير الزراعة المستدامة على تخزين الكربون العضوي في التربة. حيث يؤدي تدهور التربة الناتج عن الممارسات الزراعية إلى تدمير تجمعات الصغرى المغلفة للكربون العضوي وبناء التربة. مما يعرض الكربون القابل للتغير في هذه التجمعات للتفاعل الميكروبي. أيضاً وجدت الدراسة الحالية، أن تغيير الكربون العضوي بالتربة يؤثر بشكل كبير بالمدخلات العضوية كعمليات الخدمة العضوية مثل الجسيمات النانوية العضوية (CNPs) خاصة في التربة الرملية، والطينية الفقيرة في محتواها من المادة العضوية.