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Cotton plant (*Gossipyum* spp.) development and yield are influenced by soil compaction: A Review

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Abstract

Intensive exploitation of soils has resulted in physical, chemical, and biological degradation as the demand for agricultural *commodities*, including cotton, has grown. Physical characteristics of the soil are those that are directly linked to the supply of water, nutrients, and air, as well as the establishment of roots for good agricultural crop development and yield. In this context, soil compaction is one of the most serious environmental issues caused by conventional agriculture. Cotton plant, which is highly sensitive to water stress and lack of soil aeration, is directly impacted by this type of degradation, which results in reduced root system development, affecting water and nutrient absorption, and causing damage to overall plant and crop yield. Soil compaction has been shown to reduce cotton yield in several studies; for example, the majority of the southeastern cotton-growing regions in the United States, which make up the majority of the U.S. Cotton Belt, have compacted soils and 66 % of cotton farmers in Australia were affected by soil compaction, while other research shows a 27 % yield loss for the crop in these conditions. On the other hand, most studies carried out in systems that aim to reduce soil compaction, have shown that improvements in soil physical properties related to decompaction result in an increase in cotton plant yield.
Keywords: aeration; cotton; *Gossypium hirsutum* L.; hydric stress; soil physical properties.

O desenvolvimento e a produtividade do algodoeiro (*Gossipyum* spp.) são influenciados pela compactação do solo: Uma Revisão

Resumo

A exploração intensiva dos solos resultou em sua degradação física, química e biológica à medida que a demanda por *commodities* agrícolas, incluindo o algodão, cresceu. As características físicas do solo são aquelas que estão diretamente ligadas ao fornecimento de água, nutrientes e ar, bem como ao estabelecimento de raízes para o bom desenvolvimento e rendimento das culturas agrícolas. Nesse contexto, a compactação do solo é um dos mais graves problemas ambientais causados pela agricultura convencional. O algodoeiro, altamente sensível ao estresse hídrico e à falta de aeração do solo, é diretamente impactado por esse tipo de degradação, que resulta na redução do desenvolvimento do sistema radicular, afetando a absorção de água e nutrientes e causando danos ao rendimento geral da planta e da lavoura. A compactação do solo demonstrou reduzir o rendimento do algodão em vários estudos; por exemplo, a maioria das regiões produtoras de algodão do sudeste dos Estados Unidos, que compõem a maior parte do Cinturão do Algodão do país, têm solos compactados e 66 % dos cotonicultores na Austrália foram afetados pela compactação do solo, enquanto outras pesquisas mostra uma perda de rendimento de 27 % para a cultura nestas condições. Por outro lado, a maioria dos estudos realizados em sistemas que visam reduzir a compactação do solo, tem mostrado que melhorias nas propriedades físicas do solo relacionadas à descompactação resultam em aumento da produtividade do algodoeiro.
Palavras-Chave: aeração; algodão; *Gossypium hirsutum* L.; estresse hídrico; propriedades físicas do solo.

Introduction

Cotton (*Gossypium* spp.) is one of the world's most important fiber crops, with 35 million hectares planted annually in more than 60 countries on average (SHAHBANDEH, 2021; ABRAPA, 2021). The global cotton trade is worth about $12 billion per year, and demand has been rising steadily since the 1950s, with an average annual growth rate of 2 % (ABRAPA, 2021). The increased demand for food, fibers, and energy changed the landscape, and Brazil established itself as a major producer and exporter of cotton on a global scale (RAMOS *et al.*, 2021), becoming one of the world's top five cotton producers, presenting the highest yield in rainfed among the main producing countries (CORDEIRO *et al.*, 2022). Mato Grosso stands out among Brazilian states as the country's largest cotton producer, with a cultivation area of approximately 1,6 million hectares and a production of 1.8 million tons of lint, followed by Bahia, which has 332 thousand hectares and a production of 597 thousand tons of cotton lint (ABRAPA, 2021; CONAB, 2022).

Intensive exploitation of soils has resulted in physical, chemical, and biological degradation as the demand for agricultural commodities, including cotton, has grown (ANGHINONI *et al.*, 2019; ANGHINONI *et al.*, 2021). Physical characteristics of the soil, especially compaction, are those that are directly linked to the supply of water, nutrients, and air, as well as the establishment of roots for good agricultural crop development and yield (TOPP *et al.*, 1997; BLANCO-CANQUI *et al.*, 2011; MCKENZIE *et al.*, 2014). In this context, soil compaction, which is characterized by increased soil density and consequently reduced pore sizes, is one of the most serious environmental issues caused by conventional agriculture, but it is also the most difficult type of degradation to diagnose. (HAMZA; ANDERSON, 2005).

Cotton is a crop native to a tropical climate that has a moderate tolerance for water stress during vegetative growth but is extremely sensitive to it during reproductive growth (WANG *et al.*, 2016; NIU *et al.*, 2018). Photosynthesis, stomatal conductance, ATP synthesis, and carbohydrate metabolism are all reduced by water stress, resulting in lower biomass production (UL-ALLAH *et al.*, 2021). Several cotton-producing regions are experiencing water shortages, and climate projections show that droughts will become more frequent and intense in the future (WANG *et al.*, 2016). In this way, climate change, in combination with soil compaction, will be able to impact on the depth of development of cotton roots and their water supply throughout their life cycle, lowering yield and fiber quality.

In light of the foregoing, the aim of this review is to see how the compacting of the soil affects the development and yield of the cotton plant. For that, Scientific databases PubMed, EBSCOhost, Science Direct, Scopus, and Google Scholar were used to conduct a literature search and collect data for this review. Were primarily considered relevant full-length articles published in peer-reviewed journals in English between 2000 and 2022, but relevant works from earlier periods were also considered in Portuguese.

Conference abstracts, preliminary results and unpublished results were excluded. *Gossypium*; *Gossypium* spp; *Gossypium hirsutum* L; Soil Compaction, Soil Physical Properties, Soil Aeration were among the keywords used in various combinations. We also looked through the primary literature bibliography to find more relevant articles.

Cotton Growing

The genus *Gossypium*, which belongs to the Malvaceae family, contains 52 species, but only four are commercially grown: *G. hirsutum*, the most widely cultivated species, *G. barbadense*, *G. herbaceum* and *G. arboreum* (CHIAVEGATO, 2009). Cotton is a perennial crop, with an indeterminate growth habit, that is grown as an annual crop in mechanized production lines and systems in tropical and subtropical regions (CONSTABLE; BANGE, 2015; GWATHMEY *et al.*, 2016). The crop's indeterminate growth means that all main branches, both vegetative and fruiting, terminate in a vegetative bud (CHIAVEGATO, 2009; CONSTABLE; BANGE, 2015), where cotton fruits and vegetative growth occur at the same time, posing crop management challenges in terms of water and nutrient availability for balanced vegetative and reproductive development (HEARN, 1975; CONSTABLE; BANGE, 2015). Even after thousands of years of domestication and hundreds of years of reproduction, the cotton plant can lose a large proportion of its fruits and revert to a primarily vegetative growth depending on climatic conditions and management, in a phenomenon called shedding (CHIAVEGATO, 2009; CONSTABLE; BANGE, 2015).

Cotton's complex development over time and space necessitates a delicate balance of climatic and management factors in order to achieve an adequate balance of vegetative and reproductive growth (GWATHMEY *et al.*, 2016). In this way, an excess of vegetative development causes a delay in maturation and increases pest, disease, and fruit rot problems in the plants' middle and lower thirds (CHIAVEGATO, 2009). Excess fruiting, on the other hand, can speed up the crop cycle, lowering yield and fiber quality (CONSTABLE; BANGE, 2015; GWATHMEY *et al.*, 2016).

Cotton development is divided into four stages based on their phenological bases: vegetative, flower bud formation, flower opening, and boll opening (ROSOLEM, 2001; CHIAVEGATO, 2009). The vegetative phase begins with the emergence of seedlings and lasts until the first floral button appears. 70 % of the plant's energy is used to develop the root system during this time, resulting in a gradual increase in the number of leaves and the development of nodes and internodes. Depending on the cultivar, this phase can last anywhere from 35 to 45 days. Beginning with the appearance of the first visible flower bud and ending with the opening of the first flower, the flower bud phase is the beginning of the cotton reproductive period. With this, begins the flowering phase begins, and ends with the opening of the first boll; it is at this point that the plant has the highest demand for water supply. Water stress during the flowering phase can cause flower buds and apples to fall off, reducing cotton yield. When the first apple of the first fruiting branch turns into a boll, the boll opening stage begins (ROSOLEM, 2001; CHIAVEGATO, 2009).

Cotton is one of the world's most important agricultural crops, cultivated in more than 60 countries, with China, India, the United States, Pakistan, and Brazil accounting for more than 80 % of global production (SHAHBANDEH, 2021; ABRAPA, 2021). The product with the greatest commercial interest is fiber, but the use of crop grains, which provide about 10 % of the harvest's gross profit, depending on relative lint prices (SANTOS *et al.*, 2020), is important for production of oil and animal feed (CORDEIRO *et al.*, 2022). When the cotton seed yield is added to the lint, the harvest rate rises to around 60 % (CONSTABLE; BANGE, 2015). Brazil has higher cotton yield in rainfed systems, with fiber yields greater than 40 % (SANTOS *et al.*, 2020; CORDEIRO *et al.*, 2022) and the crop's productive potential is maximized in fertile soils with high levels of organic matter, deep soils with an adequate balance between water availability and soil aeration, (SANTOS *et al.*, 2020).

Some ancient cotton species evolved in very dry environments and can survive long periods of water deficit, while the dominant commercial species, *Gossypium hirsutum*, is native to tropical regions and responds positively to water supply (CHIAVEGATO, 2009; CONSTABLE; BANGE, 2015; GWATHMEY *et al.*, 2016). Water stress reduces yield by 19 kg ha^{-1} for each day of stress during flowering in commercial production systems, with stress interactions at different growth stages resulting in large cumulative yield losses (KULKARNI *et al.*, 2010). Water deficit from the vegetative stage to the opening of the first flower increased the drop of buds and changed the distribution of bolls on the plant, according by Echer *et al.* (2020). In this way, aspects of the soil's physical, chemical, and biological health will have an impact on fiber yield in this way, and these conditions must be properly diagnosed in order to minimize and prevent impacts on the cotton crop (KULKARNI *et al.*, 2010; SANTOS *et al.*, 2020; RAMOS *et al.*, 2021).

Soil physical quality

The soil quality is defined as ability of a soil to function within an ecosystem and land use boundaries, sustain biological yield, maintain environmental quality, and support human health and housing (DORAN; PARKIN, 1994). Assessing soil quality is crucial for detecting problem areas, determining sustainable agricultural management, and detecting early warning signs of negative trends (OJO *et al.*, 2022). Due to demographic pressures, limited agricultural land availability, and high rates of nutrient depletion, the impacts of agricultural land use on soil quality have received a lot of attention in recent years (OJO *et al.*, 2022).

Soil quality assessment has become a important method for determining the effects of land use on the soil's ability to maintain or lose its productive capacity (BLANCO-CANQUI *et al.*, 2011; BLANCO-CANQUI; RUIS, 2018). Physical quality stands out among the soil quality properties because it is linked to root development and the flow and storage of air and water in the soil, both of which affect nutrient absorption and plant growth, being defined as the capacity of a given soil to meet the water, aeration, and resistance needs of plants and the ecosystem over time, as well as to resist and recover from processes that might reduce this capacity (MCKENZIE *et al.*, 2014, SHAHEB *et al.* 2021).

As highlighted by Reynolds *et al.* (2002), a good physical quality agricultural soil is one that is heavy enough to maintain a good structure, allow for crop establishment, and resist erosion and compaction while also being soft enough to allow for unrestricted root growth and the proliferation of soil flora and fauna. Soils with good physical quality have fluid transmission and storage characteristics that allow the proper proportions of water, dissolved nutrients, and air to be delivered to crops while minimizing environmental degradation (TOPP *et al.*, 1997; REYNOLDS *et al.*, 2002).

Modernization of mechanization has increased agricultural yield, improving the efficiency of operations and reducing labor costs (FERREIRA *et al.*, 2020), however, larger machines with greater capacities tend to increase soil compaction, reducing soil quality and, consequently, affecting crop yield (MARTINEZ *et al.*, 2016; FERREIRA *et al.*, 2020; GHARAKHANI *et al.* 2022). In addition to machinery, natural soil formation characteristics, which cause dense layering at shallow depths and soil contraction due to the drying process, can also cause compaction (LIPIEC *et al.*, 2012).

Soil compaction hinders nutrient transport in the root zone and has a negative impact on crop development, water flow, yield, and root development and distribution (HAMZA; ANDERSON, 2005; LIPIEC *et al.*, 2012). Soil compaction, in any level, reduces pore size and creates unconnected pore space, making root growth more difficult, reducing soil water infiltration, and reducing aeration (BLANCO-CANQUI *et al.*, 2011; SHAHEB *et al.* 2021). It's timely to point that a penetration resistance of 2.0 MPa is considered critical to the growth of most crop plants (TAYLOR; GARDNER, 1963).

Fiber production, fiber yield, and seed cotton production are all influenced by soil physical properties, according to several authors (NOURI *et al.*, 2018; ANGHINONI *et al.*, 2019; NOURI *et al.*, 2019), such as the soil's texture (CORDEIRO *et al.*, 2022), total porosity, macroporosity and microporosity (NOURI *et al.*, 2018; ANGHINONI *et al.*, 2019; NOURI *et al.*, 2019). The physical attributes of the soil also alter the absorption of nutrients by the cotton plant (RAMOS *et al.*, 2021; CORDEIRO *et al.*, 2022). In this context, it's critical to comprehend the relationship between soil physical characteristics and their impact on cotton fiber yield and quality (RAMOS *et al.*, 2021).

Soil physical quality and cotton yield

Cotton is typically grown in clay-right, water-holding soils (CORDEIRO *et al.*, 2022) and the operations carried out during the crop cycle may cause soil compaction. Subsoil compaction provided by intense agricultural mechanization (MARTINEZ *et al.*, 2016; FERREIRA *et al.*, 2020; AL-SHATIB *et al.*, 2021) can reduce cotton yields by 35 % (DANIELLS, 1989). In this context, 66 % of cotton farmers in Australia were affected by soil compaction (CCA, 2020), with emphasis on the Vertisols areas (AL-SHATIB *et al.* 2021). McGarry (1990) discovered that cultivating in soil with too much moisture resulted in a 30 % reduction in aeration porosity, which had a negative impact on the crop's development. By restricting root growth, soil compaction can affect water and nutrient use efficiency. (FALKOSKI FILHO *et al.*, 2013; JAMALI *et al.*, 2021), that said, McGarry (1994) discovered that for maintaining fiber yield in a compacted soil, required three times the number of irrigations, significantly reducing water efficiency and increasing production costs.

Kulkarni *et al.* (2010) conducted experiments, in three successive years, evaluating four treatments, control (no subsoiling, CL); conventional (subsoiled, disked, and bedded, CDB); sub-soiled and compacted (CC) by running a backhoe weighing 6681.8 kg once on subsoiled plots. The authors observed a significant yield reduction as an indicator that vehicle traffic over successive years tends to build compaction, and it will have a cumulative effect on crop performance if not addressed, suggesting that subsoiling strategies could be planned based on yield impact observed in the field at the second or third year in monoculture fields.

Aiming at investigating the relationship between yield, plant stress time and changes in soil water at specific depths, Jamali *et al.* (2021), found that soil compaction resulted in a loss of cotton yield by 27 %. According to the authors, the decrease in cotton yield was caused by inefficient water use in the 0.30-0.50 m layer, indicating that physical barriers to cotton root penetration in this layer hampered water absorption by the roots. Compaction can cause L-shaped roots in cotton, where roots grow laterally into the "softer" soil above the compacted layer, due to the physical impediment to root development caused by compaction. According to some studies, the accumulation of ethylene, which acts as a signal to the plant root not to develop in that layer, may inhibit root elongation in compacted soils (GAO *et al.*, 2015; VANHEES *et al.*, 2021).

To obtain water and nutrients from the soil, roots must be able to withstand biotic and abiotic stresses. The soil's penetration resistance is one of the most significant constraints on root growth and function. Root growth restrictions result in morphological changes such as increased root diameter and the formation of twisted roots. Cotton, compared to the majority of other crops, has been show up to be more sensitive to soil compaction (SILVA *et al.*, 2006).

Falkoski Filho *et al.* (2013) looked at the impact of increasing root penetration resistance in five different cotton cultivars (FMT 701, FMT 705, FMT 707, FMX 966 LL, and FMX 951 LL) e they found that que cotton cultivars showed minimal variability in sensitivity to soil high penetration resistance. However, in terms of dry matter production, cultivar FMT 707 showed the most sensitive and cultivar FMT 701 showed the highest tolerance to soil compaction. In this case, the shoot development of the cultivar FMT707 was hampered, with an average reduction of 38 % due to increased soil compaction. Furthermore, at a penetration resistance range of 0.92–1.06 MPa, a 50 % growth loss was observed. Increased compaction in depth hampered root growth in the majority of the cultivars tested by the authors, increasing root diameter in some cases. On the other hand, according to Rosolem *et al.* (1998), root growth in cotton plant can occur up to 2.45 MPa of penetration resistance, whilst Coelho *et al.* (2000) reports thar cotton roots were found under a layer with a resistance of 3.0 MPa. However, it's worth pointing that these figures don't necessarily imply that the total volume of roots and crop cotton yield are not unaffected.

In the same way, according to Silva *et al.* (2006), soil compaction at depth affects the development of cotton plant aerial part, and increasing soil density reduces water consumption by the plant by 52 %. It's worth pointing that limiting root development means the plant's ability to capture the resources it needs to grow and develop is limited, resulting in a low crop yield.

According to several authors, subsoiling helps to reduce soil compaction and can lead to increased root growth in cotton yield (SCHWAB *et al.*, 2002; BUSSCHER; BAUER, 2003). On the other hand, evaluating systems aimed at reducing soil compaction, Nouri *et al.* (2019) observed average yield of cotton fiber 12 % higher in soils under no-tillage system (NTS) compared to the conventional tillage system (CTS), and point out that this was due to an increase in biopores, which increased water infiltration in the NTS and, as a result, soil water storage, a trend similar to that observed by Jabro *et al.* (2021), in soil classified as Dooley sandy loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls) derived from glacial till parent material. Delaune *et al.* (2019) observed that wheat as a cover crop reduces soil compaction by reducing density, improving pore distribution, increasing infiltration, and, as a result, soil water storage, resulting in an increase in cotton crop yield. Similar results were obtained by Nouri *et al.* (2020), with increases in cotton yield of 13 to 17 % in systems that aim to improve the physical quality of the soil through the use of plant covers. Cotton is a sensitive crop to "waterlogging" or limited aeration (anoxic stress), which results in a decrease in yield due to the loss of reproductive organs (NIU *et al.*, 2018; UL-ALLAH *et al.*, 2021). This limiting context tends to occur due to soil compaction, which increases the volume of micropores and, as a result, reduces aeration. This way, reducing compaction and improving the distribution of soil pore space, the cotton plant to withstand longer periods of drought is. This allows the cotton plant to develop deep roots, which favors the absorption of water and nutrients in deeper layers of the soil. Fiber production increased from 560 kg ha^{-1} in bare soil to 850 kg ha^{-1} in soil covered with plant debris in rainfed cultivation (BAUMHARDT *et al.*, 2013), owing, mainly to increased water storage in the soil. Several authors have observed a positive response of cotton yield in systems aimed at improving soil physical properties (HULUGALLE *et al.*, 1997; HULUGALLE; SCOTT, 2008; ANGHINONI *et al.*, 2019; NOURI *et al.*, 2019; CORDEIRO *et al.*, 2022).

Conclusion

Soil compaction affects the growth of cotton, causing a reduction in root development, impeded water and nutrient absorption, and, as a result, a decrease in crop yield in a range of 27 to 35 %, In addition to lowering the efficiency of water use in irrigated systems.

It's worth noting that conservationist systems, combined with cover crops aimed at reducing compaction, significantly improve cotton development while lowering productions costs.

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