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Photograph: Keshav Kranthi, ICAC

Editorial

This issue of the ICAC RECORDER attempts to investigate the carbon world of cotton, its water usage and the promise of nano technologies for cotton fabrics. Life cycle assessment (LCA) studies attempt to estimate greenhouse gas (GHG) emissions and carbon sequestration (to some extent), but the verdict is unclear, hazy and amorphous. Unfortunately, a review of the available information doesn't provide a clear inference on whether cotton is carbon neutral or carbon negative or carbon positive, mainly because of the uncertainties related to the estimates of carbon sequestration rates. The current predicament highlights the need to develop methodologies to estimate the net carbon sequestration potential of all crops including cotton.

The UN Climate Change Conference of the Parties (COP26) held in Glasgow, Scotland in November 2021 asked countries to come forward with 'emission reduction targets for 2030' that align with reaching net-zero emissions by 2050 to keep 1.5 degrees or less of global warming within reach. Countries were asked to accelerate the phase-out of coal, curtail deforestation, encourage investment in renewables, protect and restore ecosystems and build resilient infrastructure and agriculture to prevent loss of homes, life and livelihoods. Undoubtedly, it is time to act. Agriculture emits 9.3 Giga tonnes (Gt) of carbon dioxide equivalent (CO_2eq) GHGs every year (Source: FAO, 2021). GHG emissions (CO_2eq) in agriculture come mainly from livestock and manures (2.9 Gt), nitrous oxide (2.1 Gt), crop residue burning (1.8 Gt), deforestation (1.1 Gt), in addition to 0.7 Gt each from crop lands and rice cultivation and 0.05 Gt from grasslands. Nitrogenous fertilisers used in agriculture are the main sources of nitrous oxide emissions. Producing nitrogenous ammonia fertiliser accounts for about 1% of all global energy use (source: www.bbc.com).

The use of irrigation water and synthetic chemicals such as fertilisers and pesticides results in higher production of food, feed and fibre, but it also produces greenhouse gases. Cotton is frequently demonised for its water consumption and for the synthetic chemicals used in its production. Cotton production systems are vilified for the 57.2 million tonnes of greenhouse gas emissions it produces, but that ignores the fact that the crop has excellent potential to sequester huge amounts of carbon in its leaves, stalks, roots, seeds and fibres. It is not clear as to what purpose it may serve to attack cotton, which in many ways discourages consumers from using cotton, thus helping the cause of synthetic fibre manufacturers. One of the most common attacks comes from the proponents of organic cotton who generally build a case for organic cotton on a foundation of environmental negatives of conventional cotton. It's true that organic cotton may have a better environmental profile compared to conventional cotton, but in the long run a tirade against conventional cotton unfairly maligns the commodity itself, thereby inadvertently creating a platform in favour of synthetic textiles such as polyester.

Every fibre, irrespective of its source, has its own functional place in meeting human needs. Synthetic fibres have advantages over cotton in some respects while cotton scores better in others. But the question is: Is polyester better for the environment than cotton? The fact is that the two fibres are as different as chalk and cheese when it comes to their environmental profiles. Cotton production systems release GHGs but also concomitantly absorb huge amounts of CO_2 from the atmosphere, whereas polyester and other synthetic fibres only burn fossil fuels to emit GHGs and do not absorb CO_2 or any other GHGs from the atmosphere like cotton does. Moreover, unlike bio-friendly natural fibres, synthetic fibres are non-biodegradable and cause accumulation of micro-plastics in our ecosystems, including our food chain.

Cotton production averaged at 25.6 million tonnes over the past decade, while polyester production increased from 36.2 million tonnes in 2010 to 57.1 million tonnes in 2020. Over the past 20 years, the share of cotton in global textiles has declined from 40% in 2000 to 24% in 2020. This trend could continue unabated if the tirade against cotton continues. A study by Kirchain and others from the Materials Systems Laboratory, 2015, reported that the polyester production of 48 million tonnes in 2015 emitted 706 million tonnes of CO_2eq GHGs, which when extrapolated could be 838 million tonnes of CO_2eq GHGs in 2020 from 57 million tonnes of polyester production. Contrast this with the 57.2 million tonnes of CO_2eq GHGs from cotton fibre production, to appreciate why the tirade on cotton is unfair. Polyester is non-bio-degradable and does not absorb carbon unlike cotton. Cotton is biodegradable; it absorbs 366 million tonnes of CO_2 from the atmosphere during photosynthesis and may lock about 2% to 2.5% of carbon into the soil. Unfortunately, there are virtually no precise estimates of the net carbon balance in cotton ecosystems to fortify a robust argument in favour of the carbon-negative case of cotton production systems.

Textile production emits 1.2 billion tonnes of CO_2 equivalent greenhouse gases. Rice production alone is estimated to release about 625 million tonnes of CO_2 equivalent greenhouse gases that account for 1.3% of the total global GHG emissions.

We can't stop growing rice or wearing clothes, so what, then, is the purpose of auditing? Quantifying GHG emissions and auditing carbon dynamics through LCAs help us to identify key emission sources and develop action plans to reduce GHG emissions coupled with enhancement of carbon sequestration. The three articles published in this current issue discuss cotton-related GHG emissions, carbon sequestration, water usage and nanotechnologies. I hope that these articles will stimulate researchers to develop reliable methods to estimate the footprints of carbon and water in cotton production systems to render them more sustainable.

– Keshav Kranthi

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A Mini-Review on Recent Advances in Nanotechnology Applications with Reference to Cotton

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Dr. N. Vigneshwaran, Principal Scientist at ICAR-CIRCOT, Mumbai, India finished his Doctorate at Indian Institute of Technology, Delhi in 2005 in molecular biology towards fabrication of fiber optic-based biosensor. He initiated microbial synthesis of nanomaterials at ICAR-CIRCOT, Mumbai in 2005 and developed protocols for finishing of cotton by nano-silver and nano-zinc oxide to impart antibacterial and UV protection properties. The process of Nano-zinc oxide production was commercialized to a chemical company at Chennai, India in 2007. Later, he focused on energy-efficient nanocellulose production from cotton linters with a World Bank supported project (NAIP of ICAR). Dr Vigneswaran developed, a pilot plant for nanocellulose production. He successfully guided 2 scholars for Ph.D (Science) in Microbiology and 3 scholars are currently pursuing PhD under his guidance. Dr. Vigneshwaran received the NASI-SCOPUS Young Scientist Award for Agriculture in 2014; Young Scientist Award from Association of Microbiologists of India in 2018 and ICRA-Asia Young Scientist Medal in 2019.

Abstract

Nanotechnology is revolutionising the entire domain of scientific research resulting in unveiling of novel and unexpected products in the markets. The impacts of nanotechnology were felt earlier in the textile industry followed by pharma, electronics, energy, transportation, robotics, pulp and paper, food and health, as well as agriculture and allied sectors. As early as 1998, a company called Nanotex® was founded to replicate the natural water repellence of plant surfaces on the surfaces of textile materials. Today, the impact of nanotechnology is felt in all areas of cotton — breeding of cotton for targeted modifications, nano-fertigation, nano-pesticide applications, nano-sensors for precise farming, nano-clays and nano-hydrogels for soil improvement, nano-finishing of cotton textiles and production of nanocellulose from cotton fibres. This review focuses only on the application of nanotechnology on processing of cotton fibres/yarns/fabrics in the textile sector.

Nanotechnology

Nanotechnology refers to the manipulation of materials in the nano-size range for desired properties. The nano-size range mainly denotes 1 to 100 nanometres (nm) while a higher range is also included if the material is polymeric. The main concept is that the material should exhibit size-dependent properties in the defined size range. The size-dependent properties include surface area to volume ratio (SAR), surface plasmon resonance, quantum confinement effect, super conductivity, super para-magnetism, etc. Except SAR, other properties are also dependent on the composition of materials. Hence, based on the requirement, the specific material needs to be identified and produced in a nano-size range for specific applications. Followed by the selection of material, the methodology for conversion to the nano-form needs to be finalised. Two major approaches are available for the production of nanomaterials: The first is a top-down approach, in which the bigger particles are reduced in size to form nanomaterials; the second is a bottom-up approach, in which the atoms/ions are aggregated in controlled manner to produce nanoparticles. Both approaches have their own pros and cons. In the top-down approach, the process is simple, yield is very high and hence, easily scalable on an industrial scale; however, the quality of the product is low due to wide-size distribution. In the bottom-up approach, though a narrow size distribution of particles is obtained, the yield is very low and hence, scalability is very difficult.

Classification of Nanomaterials

Nanomaterials, based on their dimensions, are classified as 0D, 1D and 2D. The 0D includes nanoparticles in which all their three dimensions are restricted within the nano-size range. The 1D includes nanomaterials in which two dimensions are restricted within the nano-size range and the third may be of higher size; examples include nanotubes, nanorods and nanowires. The 2D includes nanomaterials having only one dimension restricted in nano-size range and the other two dimensions are of any size; examples include thin films and nano-layers. An entirely different class of nanomaterial is nanostructures, in which the object will be of macro-size and the features in that object shall fall in the nano-size range. A broad classification is given in Figure 1 is a modified version from an earlier reference (Gubala et al. 2018).

nanomaterials. XRD analysis reveals the crystal size and crystallinity of nanomaterials. SAXS is used to measure the size, shape and internal structure of the nanomaterials. AFM is also used for analysing the mechanical and chemical properties of nanomaterials in addition to their size analysis. Apart from these specialised measurement techniques, routine physical and chemical measurement techniques are used to characterise nanomaterials.

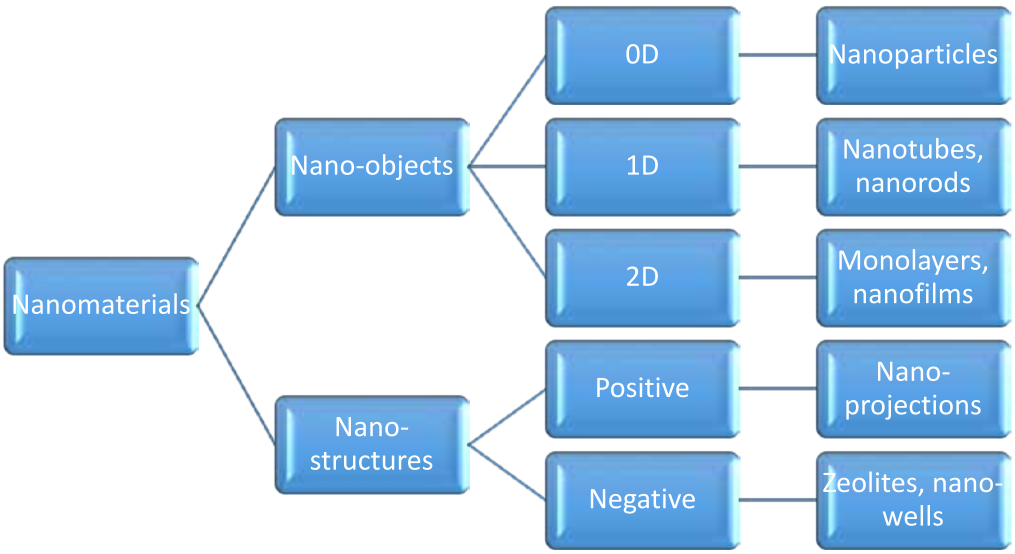

Figure 1. Classification of nanomaterials

Need for nanotechnology in cotton textiles

The impact of nanotechnology in cotton textiles started two decades ago with a promise to impart novel and efficient characteristics for cotton materials. Though cotton is the king of fibres, it has many drawbacks when compared to its synthetic counterparts. The major problems faced in cotton textiles include microbial attack and corresponding odour development, wrinkle development on usage, lack of hydrophobicity and UV transparency. These problems restrict the use of cotton in sportswear, medical textiles, agro-textiles and other technical textiles. Though many chemical and polymeric finishing agents are available to overcome a few of the above mentioned problems, they do have their own limitations. Nanomaterials are now being used to impart the desired functionalities to cotton.

Based on the source of formation, the nanomaterials are classified as naturally available, incidental/accidental and engineered nanomaterials. Another way of classifying nanomaterials is based on their chemical compositions — metals, metal oxides, ceramics, organic, polymeric and carbon nanomaterials. Based on multiple components of nanomaterials, they are also classified as core-shell, core-sheath, binary, tertiary, composites and hybrid nanomaterials.

Synthesis and characterisation of nanomaterials

Similar to synthesis, the characterisation of nanomaterials is also technically demanding and a tedious process. Since nanomaterials have very high surface energy, they tend to aggregate or agglomerate making it difficult to study their individual properties. Therefore, strategies are required to maintain the size of nanomaterials by avoiding the aggregation or agglomeration. Generally, stabilisers are used for this purpose and the principle involves imparting ionic charges on the surface of nanoparticles or coating with a polymer or both. The use of stabilisers also interferes with characterisation. The standardised size measurement techniques include DLS (dynamic light scattering) analysis, AFM (atomic force microscopy), SEM (scanning electronic microscopy) and TEM (transmission electron microscopy). The surface charges are measured by DLS and titrimetric techniques. BET (Brunauer–Emmett–Teller) analysis helps to measure the surface area and porosity of the

Antimicrobial finish

Our research team at ICAR-CIRCOT in Mumbai developed a novel green process for the production of stable nano-silver stabilised by soluble starch (Vigneshwaran et al. 2006c) and also demonstrated an *in-situ* process for application of nano-silver on the surface of cotton to impart antibacterial activity (Vigneshwaran et al. 2007). The production process was considered as environmentally 'green' because harmful chemicals were avoided in the protocols and only green chemistry was used in the synthesis protocol. The major problem during the application is binding of the nanoparticles to the surface of cotton fibres since they do not have any affinity. A simple option could be the use of textile binders to assist cotton fibres to hold the nanoparticles, but the antibacterial efficiency gets affected. Latest research evaluates the use of carboxymethyl chitosan and l-cysteine to improve the surface affinity of cotton fabrics to nano-silver (Xu et al. 2019). The *in-situ* synthesis process helps to avoid the use of binders (Montazer et al. 2012; Vigneshwaran et al. 2007) but the nanoparticles located deep inside the cotton fibre may not participate in the antibacterial activity. Figure 2 shows the photos of cotton fabrics treated with nano-silver. The colour of the fabric is due to the surface plasmon resonance property of nano-silver. The mode of action of nano-silver is due to the release of silver ions and their binding with the essential proteins of microorganisms. Apart from nano-silver, nano-ZnO (Vigneshwaran et al. 2006b), nano-lignin (Juikar and Vigneshwaran 2017), nano-copper oxide (Bashiri Rezaie et al. 2018) and nano-chitosan (Hebeish et al. 2013) are also reported to show antibacterial properties on cotton textiles.

Figure 2. Cotton fabric treated with nano-silver (light brown above). The colour is due to the surface plasmon effect of nano-silver.

UV-resistant finish

Having a UV-resistant finish helps cotton fabrics restrict the entry of UV rays. Conventionally, various chemical finishing agents and dark-coloured dyes are used to restrict the entry of UV rays. With the developments in the use of nanomaterials, the requirement of pigments has drastically reduced without affecting their activity. Nano-ZnO and nano-titania are the well-demonstrated nanomaterials being used for UV-resistant finishes. Our research group worked on the production of nano-ZnO by reacting zinc nitrate with sodium hydroxide in the presence of soluble starch resulting in the nanoparticle size of 38 ± 3 nm (Vigneshwaran et al. 2006a). This nano-ZnO, after applying to the surface of cotton fabrics, imparted excellent antibacterial and UV-resistant properties. Figure 3 shows the scanning electron microscopic view of nano-ZnO deposited on the surface of cotton fibres. The UV-absorbing property is mainly due to the semi-conducting property of metal oxide nanoparticles like nano-ZnO and nano-titania. The band gap in these nanoparticles is sufficient enough to absorb the UV rays. Knitted cotton fabrics with nano-ZnO showed moderate to high ultraviolet protection factor (UPF), while 50+ UPF value was achieved in case of nano-titania (Paul et al. 2010). Also, this work reported that the rutile phase of titania was better than anatase phase in blocking UV rays. Another study demonstrated that the use of dumbbell-shaped nano-ZnO exhibits better UV-absorbing property after application on the surface of cotton fabrics (Wang et al. 2005). Ag/ZnO nanocomposite was applied on coloured cotton fabric to impart special properties such as self-cleaning, anti-bacterial, and UV-absorbing traits (Avazpour et al. 2017). Organic nanoparticles like nano-lignin can also impart UV-absorbing property to cotton textiles (Juikar and Vigneshwaran 2017).

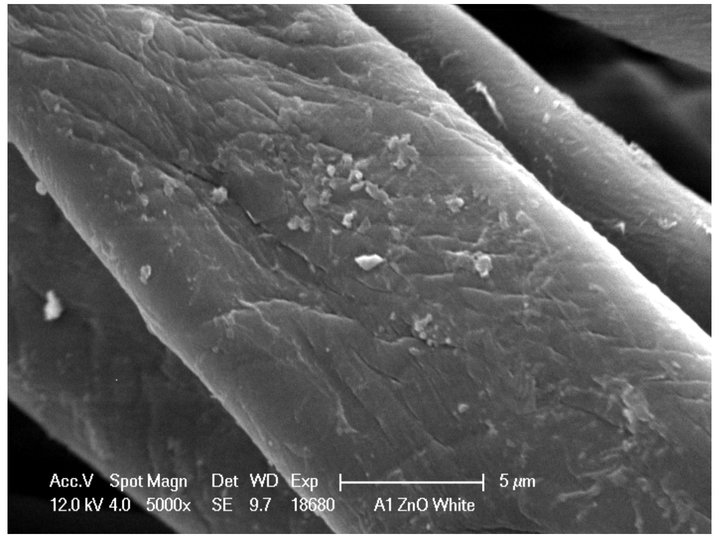

Figure 3. Scanning electron micrograph of cotton fibres impregnated with nano-ZnO

Self-cleaning property and Superhydrophobicity

Nano-titania in the size of range of 3 to 15 nm was found to impart self-cleaning properties to cotton by its photocatalytic activity to degrade methyl orange (Tan et al. 2013). The use of a stabiliser such as chitosan coated nano-titania for the nanomaterials, resulted in a reduction of self-cleaning properties from 96% to 89% due to the presence of organic coating (chitosan, in this case); however, it was compensated by its antibacterial activity (Goyal et al. 2016). The photocatalytic activity depends on the band gap of metal oxide nanoparticles which, generally fall in the UV-range. Hence, UV light is required for photocatalytic activity of nanoparticles. To overcome this issue, doped nanomaterials are being evaluated to have visible light induced photocatalytic activity. Nitrogen-doped nano-titania, synthesised by sol-gel route provides photocatalytic property without the requirement of UV radiations of high energy photons (Katoueizadeh et al. 2018). Apart from photocatalytic activity, self-cleaning property could be achieved by Lotus Effect® or superhydrophobicity. To obtain the superhydrophobic water repellent surfaces on cotton fabrics, silica nanoparticles coated with water-repellent agents are used. The water contact angle above 130° could be achieved using the combination of silica nanoparticles and water repellent agent (Bae et al. 2009). In this case, hydrophobicity was introduced by chemistry of the water-repellent agent and superhydrophobicity was achieved in combination with the effect produced by nano-architecture of the silica nanoparticles.

Flame-retardant finish

Environmental concerns of fluorinated and organophosphorus compounds result in exploration of different nano-based methodologies to impart flame retardancy to cotton textiles. The limiting oxygen index, which indicates the flame retardant property of a fabric, increased from 18.6 to 23 when the cotton fabrics were coated with sodium hypophosphite, maleic acid, triethanol amine and nano-titania (Lessan et al. 2011). Cotton functionalised with epoxy and carboxyl via grafting cotton with nano-emulsion consisting of glycidyl methacrylate and acrylic acid was treated for functional finishing by the traditional pad-dry-cure process and it resulted in excellent flame-retardant properties (Mohamed et al. 2014). Another research group explored the use of nano-titania on cotton fabrics in the presence of poly-carboxylic acid [1,2,3,4-butane tetracarboxylic acid (BTCA)] with sodium hypophosphite as catalyst and chitosan phosphate through conventional pad-dry-cure method; this expressed flame retardancy and antibacterial properties (El-Shafei et al. 2015).

Nanocellulose from cotton

Our research team at ICAR-CIRCOT is also working towards the development of a value-added product like nanocellulose from cotton linters and other cotton wastes. Nanocellulose is an amazing material with excellent mechanical properties while retaining its organic/biodegradable nature. The standard method used most commonly deploys sulfuric acid hydrolysis process to produce nanocellulose from any cellulosic biomass including cotton (Theivasanthi et al. 2018). The acidic hydrolysis process to extract nanocellulose (177 nm long and 12 nm wide, as measured by microscopy) from cotton increases the crystallinity index and the hydrophilicity and decreases their thermal stability (Morais et al. 2013). The by-products of cotton like cotton gin motes and cotton gin waste were also evaluated for production of nanocellulose having diameters <10 nm and lengths of ca. 100–300 nm (Jordan et al. 2019). Novel eco-friendly processes for production of nanocellulose from cotton fibres were reported by our group in which cellulolytic fungus (Satyamurthy et al. 2011) and an anaerobic microbial consortium (Satyamurthy and Vigneshwaran 2013) were used to reduce the size of cellulosic particles. The primary advantage of microbial processes is their eco-friendliness, which eliminates the need for harmful chemicals, while yield and purity are the main bottlenecks to be solved. Transmission electron microscopic image of nanocellulose prepared at ICAR-CIRCOT by a chemo-mechanical process is shown in Figure 4 and the AFM image of nanocellulosic fibrils prepared by mechanical process is shown in Figure 5. ICAR-CIRCOT's unique nanocellulose pilot plant is producing nanocellulose from cotton fibres at a capacity of 10 kg per eight-hour shift and is being supplied to researchers and industries for product development.

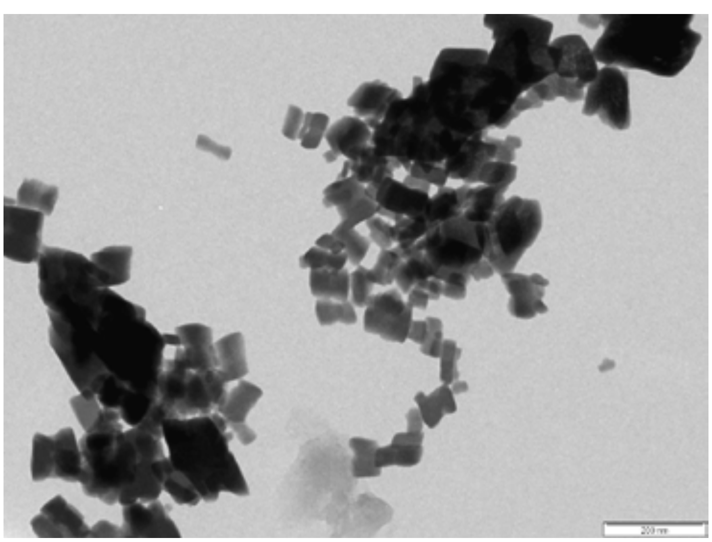

Figure 4. Transmission electron micrograph of nanocellulose nanoparticles produced from cotton linters.

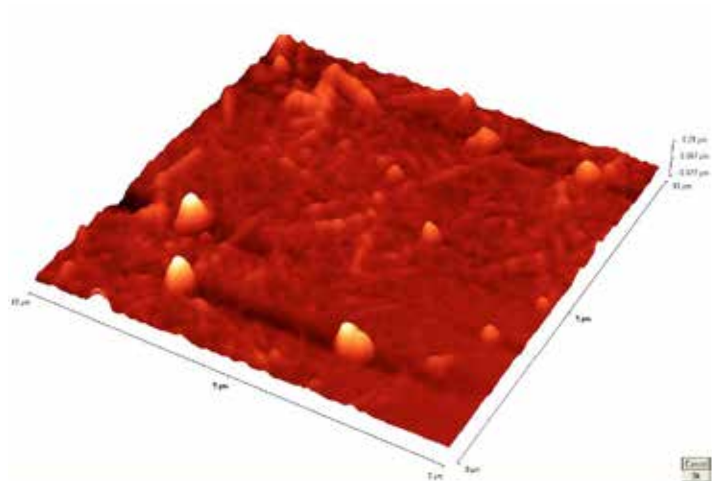

Figure 5. AFM image of cellulose nanofibres

Standards and safety

Standardisation in the field of nanotechnology is being handled by five international agencies: International Organization for Standardization (ISO), European Committee for Standardization (CEN), British Standards Institution (BSI), ASTM International and OECD Working Party on Manufactured Nanomaterials (WPMN). In addition, specific materials' standards are taken care by respective expert groups. For example, the ISO/TC 229 – Nanotechnologies expert group is being supported by TAPPI, a registered not-for-profit, international non-governmental organisation involved in the areas of pulp and paper technology for developing standards related to nanotechnology. Nanotechnology is an emergent and facilitating technology with the potential to create novel materials and products with various advantages in scientific and medical applications. The Division of Occupational Health and Safety of National Institute of Health has released the *Nanotechnology Safety and Health Program 2014* to help researchers and other stakeholders in the field of nanotechnology to familiarise themselves with safety precautions to be followed in the field of nanotechnology. Similarly, the National Institute for Occupational Safety and Health published a document titled '*Building a Safety Program to Protect the Nanotechnology Workforce: A Guide for Small to Medium-Sized Enterprises 2016*' for the benefit of people involved in nanotechnology-related enterprises. These documents are available free online and help in the research and development of nanomaterials.

Conclusions

Nanotechnology has begun to make its impact visible in the field of cotton textiles and cotton biomass utilisation. The established work force around the world is producing novel processes and products using nanotechnology for applications in cotton. Apart from solving the existing problems, nanotechnology also helps to evolve newer products and finishes in cotton textiles. With responsible use of nanotechnology, the cotton finishing and biomass value-addition sectors are bound to benefit from this revolution.

Acknowledgements

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Is Cotton a Water-Guzzling Crop? Some Principles of Cotton Water Relations

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Marcelo Paytas is the Director of INTA (National Institute of Agricultural Research) Reconquista Santa Fe, Argentina. Researcher and project leader of the cotton team with focus on crop physiology and agronomy, biotechnology and genetic improvement at INTA. Marcelo graduated as Agricultural Engineer at the National Northeast University, Corrientes, Argentina. Obtained a PhD at the University of Queensland, Australia in Cotton physiology and Agronomy. He is member of APPA (Association for the promotion of cotton production) which associates all representatives of the cotton chain of Santa Fe, Argentina. Coordinator of academic and technical agreements between INTA and other national and international organizations, mainly in South America. Member of SEEP (Social, Environmental and Economic Performance panel) of the International Cotton Advisory Committee (ICAC) and Executive Committee member of the International Cotton Researchers Association (ICRA). Dr Marcelo's main interest is to link and promote research and development together with the cotton industry through public and private interaction for sustainable production.

Water availability is potentially one of the most limiting abiotic factors for profitable cotton production. Cotton appears to be well adapted to the production of lint under a range of water regimes and is therefore able to be grown in areas throughout the world with variable rainfall and limited water for irrigation. However, adequate soil moisture through the correct timing of irrigation or precipitation events is essential for the successful commercial production of cotton. This article refers to the information presented in the cotton webinar of the WCRC-7 Monthly Plenary Lecture Series and will discuss four aspects related to water relations in cotton:

1. Water and cotton: myths or facts or misinformation?
2. How cotton deals with water availability for its growth and development
3. The main limitations for cotton production and physiological processes involved
4. Agronomical practices to circumvent water stress.

Water and cotton: myths, facts or misinformation?

There are several different sources and estimates on water consumption in cotton production worldwide. However, different stakeholders take different positions related to water use and impacts. Having reliable data makes our analysis and position stronger whether the information represents a myth, fact or misinformation. Websites and media usually take different positions related to water use in cotton:

- Negative impact on environment
- Competition for water with other cash crops
- Sustainability issues related to water wastage and energy usage
- Compromise of irrigation water with potable drinking water needs

The cotton community will have to decipher which actions it needs to develop to inform, adopt and include within the community regarding water in cotton production. It is necessary to keep working together to improve national public policies. Concerns are not limited to cotton production; they encompass water usage in all sectors including agriculture, industry, transport, infrastructure and household activities. Water is definitely essential for life and must always be part of the agenda for sustainability.

The reduction of the waterwater footprint of cotton was discussed in the Third Open Session at the 75th ICAC Plenary Meeting held in Islamabad, Pakistan, in 2016. Cotton has been criticised for the intensive use of water in its production and processing, even though 52.4% of the global cotton area is grown under rainfed conditions and the volume of water used in cotton production is only half that of rice and sugarcane.

Irrigated wheat, rice and maize consume 15%, 13% and 10% of the global irrigation water respectively, while cotton consumes about 3% (Hoekstra et al, 2011). Other sources indicate that cotton uses 1.5% of global irrigation water used in agriculture. Irrigation use differs from season to season over the years; therefore accuracy of available information from one season to the next one is essential. The environmental variability between seasons holds the key to the dynamics of crops under irrigation or rainfed and to quantify water usage.

The distribution of cotton worldwide varies across climatic regions (arid, semiarid and humid regions). The xerophytic adaptation of cotton confers a unique characteristic on water relations of the crop that is unusual if not unique among field crops. In addition, in many countries, cotton farms are located in the most extreme and water-limited environments compared to other commercial crops.

Irrigated cotton extends through America, the Mediterranean, North Africa, Asia and Australia. On the other hand, rainfed cotton is mostly located in South America, the United States, sub-Saharan Africa and India. Between these extremes, cotton is produced with supplementary irrigation (semi-arid and humid regions) in India, Australia and regions of North America (Hearn, 1994).

Cotton productivity is generally linked to irrigation facilities and availability of water when the crop needs it the most. However, higher yields are not only attributed to water, but also to the technology applied in terms of seed, management programs, irrigation systems and others.

How many litres of irrigation water do we need to produce 1 kg of lint? The ICAC data (ICAC Cotton Databook 2020) shows that an average of 1,931 litres of water were used to produce 1 kg of lint. However, information on various websites available refers to 7,000 to 29,000 litres of water to produce 1 kg of lint. These values often include green (rain) water and grey (decontamination) water. However, the estimates differ significantly, highlighting the importance of having a consistent dataset of statistics around the world.

The percentage of rainfed cotton area around the world is about 52% and 41.3% of global cotton is produced without irrigation water (ICAC). This situation is likely to change year to year depending on environmental conditions, water availability and rainfall occurrence. In some cases, supplementary irrigation might be needed. This also shows how challenging it is to produce cotton exclusively under rainfed conditions due to uncertain monsoon patterns and erratic rainfall distribution.

How cotton deals with water availability, How cotton grows and develops?

There are fundamental principles about water and cotton:

1. The xerophytic background shared with wild ancestors of cotton confers intrinsic adaptation to water deficit compared to other commercial crops.
2. Crop development stages influenced by water availability. This refers to the influence of water on cotton development with reference to the patterns of regular production of main stems, lateral fruiting branches, fruiting sites, abortions, fruit development and fibre development.Modern cotton varieties are indeterminate, with vegetative and reproductive development following an orderly and regular pattern. Vegetative growth is characterised by the successive development of the main stem (primary axis) nodes. A new node is produced every two to four days, depending on the temperature during growth (Hearn and Constable, 1984) and soil moisture availability. Axillary branches differentiate from the main stem. At the lower nodes, monopodial branches (similar to the primary axis) can develop, but from approximately the fifth main stem node and upward, only sympodial branches develop (Heitholt, 1999). Fruiting sites are produced at regular intervals, about every five to six days, along the fruiting branch (Hearn, 1994).
3. Growth physiological processes in response to water stress. This aspect is fundamental to understand when cotton is planted and how varying stages and amount of water availability can affect physiological aspects of the crop.

The concept of sensitivity to water stress (drought or waterlogging) related to crop stages is essential and includes intensity and duration of water stress. The definition of water stress includes weather vagaries, plant water content and soil moisture availability.

In terms of management, the cotton is different from most others that are normally grown as rotation crops within the farm. The water requirements and nutrient needs of cotton get accentuated during the peak boll formation stage, especially when boll-retention is high. Retention of fruits and squares greatly influences plant growth. Increased fruit retention on the plant is the best plant growth regulator for controlling plant growth. As the plant accumulates fruit load, vegetative growth slows down and finally ceases when bolls mature completely. As boll load increases, terminal growth and the production of new nodes slow and then cease. An appropriate balance between vegetative and fruiting development is essential for high yields.

Cotton is mainly cultivated to produce fibre. It is a smart plant that uses 2.25 times more energy to produce oil (seed) than cellulose (fibre). It is important to understand the target growth and development curve. This curve shows the accumulation of vegetative dry matter and the partitioning to reproductive fruiting parts. About 70% of the boll weight is accumulated after the termination of vegetative period. Any limiting situation that happens during this period with reference to heat, water and nutrient availability will be negative to cotton yield and quality. It is necessary to focus on water and nitrogen needs of the crop in this critical period in terms of agronomical management.

What does it take to obtain high yields? The population of plants per meter; the number of bolls retained per plant; and the fibre weight per seed should enhance yield and yield stability.

It is important to understand the critical stages of the crop to appreciate the effects of limiting environmental conditions on yields. The cotton plant undergoes a series of growth stages during the development from dormant seed to mature fibre. These stages are distinct but also overlap. When water supply is optimum, phenological development continues for a longer time, resulting in healthier plants and higher yields; when the supply is limiting, the opposite occurs. The key adaptation of the cotton plant is that when water supply starts to become limiting, the plant responds to stop further morphological development and focuses on the maturation of fruit already set. During the vegetative stage, the consumption of water is less at 2-3 mm per day compared to the medium and later stages when the crop needs 6-8 mm per day. Cotton needs 600-700 mm of water per plant, which translates to 6-7 million litres per hectare. Depending on the type of irrigation systems used, water use efficiency (WUE) varies from 0.4 to 0.8 (kg/m3) for drip irrigation; 0.5 to 0.6 for sprinkler and 0.6 to 0.9 for furrow irrigation. The evapotranspiration rate, plant available water and soil water content are key measurement parameters to monitor and predict cotton performance (Paytas, 2013).

Figure-1 Regulating soil moisture through plastic mulches

Figure-2 Regulating soil moisture through plastic mulches

Figure-3 Aerial view of the experimental fields at INTA

Figure-4 Experiments at INTA to understand the effects of water stress on cotton under field conditions

The main limitations for cotton production and physiological processes involved

Cotton productivity can be negatively impacted by water scarcity caused by drought or flooding conditions caused by excessive rains or flood irrigation.

Drought stress

Experiments were carried out at INTA Reconquista (Argentina) to understand the effects of water stress on cotton under field conditions, using plastic mulches between rows and rainout shelters to ensure that a water-limiting factor was created. A soil-moisture meter and other equipment were used to characterise physiological processes such as photosynthesis, stomatal conductance and water potential on plants.

While cotton has a xerophytic background, the crop generally requires enough water to allow about 700 mm of evapotranspiration (transpiration plus soil evaporation) to prevent yield reductions. Scarcity of water in certain stages such as peak boll development phase can be critical for yields. Drought is defined by low soil water availability, and high evapotranspiration demand. Water stress occurs when the soil has less than 50% of field capacity. Cotton's response to stress varies on the stage of growth, the degree of stress and the length of time imposed.

When water stress was imposed during the vegetative stage, the following effects were observed:

- A reduction of plant population
- A reduction in vegetative dry matter
- Physiological processes involved in cell expansion and division were affected
- Reduction of yield due to an imbalance source to sink partitioning (about 6 kg fibre reduction per day of stress).

When the water stress was imposed during the flowering stage, the following effects were observed:

- Reduction of fruiting sites
- Abortion of flower buds
- Yield reduction and weak compensation (about 15 kg fibre reduction per day of stress);
- Poor-quality fibre.

When water stress was imposed during maturity stress, the following effects were observed:

- Boll size reduction
- Yield reduction (4-8 kg fibre reduction per day of stress)
- Early maturity
- Poor-quality fibre.

INTA conducts programmes on genetic improvement, genetic selection by molecular markers, mutagenesis for abiotic stress and higher ginning rate (ginning percentage). It is well documented that modern genotypes may show better water use efficiency (shorter period to maturity) than older genotypes (from the 80s for example).

Waterlogging

Excessive soil water availability during certain stages of the crop is considered waterlogging. Experiments were conducted at INTA Reconquista under simulated waterlogged field conditions using a non-drainage facility to study the effects of water logging on yields and fibre quality .

Cotton's response to stress varies on the stage of growth, the degree of stress and the length of time imposed. Yields were reduced by 16%-19% due to waterlogging during flowering in narrow row and conventional systems (Scarpin, 2017). Argentina produces mainly narrow row and high plant density systems.

If we consider a gradient of water available, we may understand that:

1. From excess moisture in soil, rank growth would happen.
2. From optimum irrigation towards increasing water stress, the first process affected is leaf expansion, followed by limiting fruiting sites and fibre length, with a decrease in carbohydrate production affected by weak photosynthesis and boll retention.

This situation will vary depending on the cotton stage. The sequence of the processes involved are related to crop sensitivity, starting at a cellular level, following a growth rate, leaf area index and light interception, finally affecting cotton yield. This explains the results of the experiments (shared previously) from the physiological point of view as to how varying water stress at different stages of development affects cotton yields.

As soon as available soil moisture starts to decrease, leaf expansion is the first affected and then photosynthesis. Leaf expansion will limit the sink and source assimilate relations and negatively affect fruit retention. When plants suffer a period of water deficit, leaf water potential will be affected, with reductions in photosynthesis and later on (if the stress continues) the translocation assimilates.

Long-term results of a few seasons are important to understand variability in terms of evapotranspiration rates and rainfall. A significant decrease in yield occurs in some years when the soil water deficit increases with higher evaporative demands. Thus, water management strategies vary year to year.

Agronomical practices to circumvent water stress in cotton

Appropriate agronomical practices are necessary to circumvent limiting situations for a better water use efficiency. A few such practices are listed below:

1. Crop rotation and cover crops
2. Zero tillage
3. Fertilization at sowing and pre flowering
4. Planting geometry / crop configuration
5. Sowing dates
6. Crop regulations
7. Integrated pest management
8. Integrated fibre management

The following strategies can help to achieve sustainability of cotton production systems:

- Incorporation of concepts like soil health and management, drainage systems and water-saving irrigation systems.
- Conducting further research to integrate different management aspects for cotton and other crops within the rotation for each region of production.
- Strengthening regional genetic improvement programs to obtain high yielding varieties well adapted to sub-optimal conditions and with improved water-use efficiency.
- Conducting research on cotton physiology with specific emphasis on stress physiology in each production region and the diverse environmental conditions.
- Developing training for farmers and other cotton supply chain stakeholders on aspects related to cotton production under abiotic stress.

- Invest in meteorological stations to get online historical and daily basis data related to weather in a regional scale.
- Usage indicators to estimate water footprints of the whole cotton chain for sustainable production. The Delta Project will help with indicators of sustainability.

Finally, some key important messages:

Modern varieties may have higher water use efficiency

Other commercial crops use, in some cases, more amount of water than cotton

Outstanding advances in research around the world allow us to understand water relations and efficiencies

Advanced technologies are available to enhance water use efficiency within and outside the farm

Sustainable cotton programs and existing indicators to be used for auditing and to develop actionable plans

Key statistic information must be made freely available and training of cotton stakeholders on sustainability is essential.

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Photo: Armelle Gruyère, ICAC

Cotton and Greenhouse Gases

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Introduction

Crop production practices emit greenhouse gases (GHGs) mainly comprised of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) that cause global warming. Production of food, feed and fibres are essential to meet basic human needs. With a growing population, the demand for food, feed and fibre will increase and so will the pressures on agriculture to increase production. Modern farming technologies help to increase agricultural production but these are energy-intensive and mostly chemical-dependent, which leads to increased GHG emissions. Additionally, food processing and fibre processing use synthetic chemicals, energy, electricity and water to emit GHGs. GHGs are also emitted from waste degradation in landfills which includes degradation of food waste and discarded textiles.

Cotton farming systems mainly emit GHGs due to the use of agrochemicals, degradation of soil organic matter (SOM) of crop residues or manures, or metabolism of soil microbes, and consumption of fuel and energy used for farm machinery, irrigation and transport. Farms emit GHGs but crops also capture atmospheric CO_2 for photosynthesis and store carbon in their biomass (crop residues, food, feed and fibres), to mitigate global warming and other effects of climate change. Some crops are naturally more efficient in carbon sequestration compared to others. For example, fibre crops capture CO_2 and store carbon in their fibres for a much longer time — unlike perishable fruits, vegetables and other food products — thereby exhibiting a kind of sequestration that is different from other crops. GHG emissions have been estimated in agriculture including cotton production systems. Probably due to the enormous differences in soils and production practices, which lead to uncertainties in the sequestration rates, there are hardly any estimates of the net soil carbon balance accrued from cotton crop carbon sequestration. This article attempts to review the available information on GHG emissions from cotton cultivation and fibre processing and examines the possible carbon sequestration potential of cotton farms.

Greenhouse Gases

Solar radiation is comprised of visible, ultraviolet and infrared wavelengths. The earth receives about 70% of sunlight that passes through the atmosphere and radiates it back in the form of infrared light. A few atmospheric gases act as a layer to trap heat and regulate the earth's temperature. These gas layers act like a greenhouse for the earth and are therefore called greenhouse gases (GHGs). The main greenhouse gases are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons (CFCs) and water vapour. GHGs absorb about 90% of the infrared light and reflect it back to the earth thereby causing global warming. For millions of years, GHGs were estimated to have been at levels of 200 to 280 parts per million (ppm)[1],

1) https://www.nrdc.org/stories/greenhouse-effect-101

which have now increased above 400 ppm to accentuate global warming. Higher greenhouse gas levels in the atmosphere will cause higher global temperatures[2]. The concentrations of GHGs have continued to increase in the atmosphere, reaching annual averages of 410 parts per million (ppm) for carbon dioxide (CO_2), 1866 parts per billion (ppb) for methane (CH_4), and 332 ppb for nitrous oxide (N2O) in 2019[2].

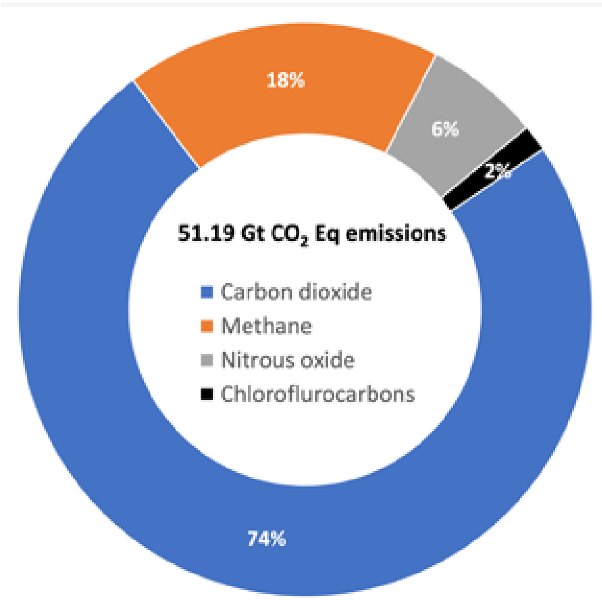

Figure-1 Global greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes in 2018 (Data Source World Bank)

Global Warming

Climate change is influenced by GHG emissions which are a consequence of human activities mainly related to the use of fossil fuels and their products in industry, electricity, transportation, lifestyle and agriculture. GHGs trap heat and cause global warming, which has a direct impact on human health, agriculture and livelihoods. In its latest sixth assessment report[3], the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN) highlighted the increasing severity of climate change impacts across the globe. The report warns that without large-scale reductions in GHG emissions, it could be beyond our reach to limit the chances of crossing the predicted global warming level of 1.5°C in the next few decades. Global warming could cause intense rainfall associated with floods in some regions and drought in others. The report provides evidence that CO_2 is the main driver of climate change, while other GHGs accentuate the impact. The IPCC Working Group-1 Co-Chair, Panmao Zhai, states[4] that "Stabilizing the climate will require strong, rapid, and sustained reductions in greenhouse gas emissions, and reaching net zero CO_2 emissions. Limiting other greenhouse gases and air pollutants, especially methane, could have benefits both for health and the climate,". The IPCC report[5] estimates that "Agriculture, Forestry and Other Land Use activities accounted for around 13% of CO_2, 44% of methane, and 82% of nitrous oxide emissions from human activities during 2007–2016, representing 23% (12.0±3.0 giga tonnes (Gt) of CO_2 equivalent GHGs per year) of the total net anthropogenic emissions of GHGs". The IPCC report also highlights the need for climate resilience through improved agricultural practices such as conservation tillage and cultivation of cover crops to enhance the soil's organic carbon content. Agriculture needs sustainable solutions to reduce pressure on ecosystems. Sustainable agricultural practices have the potential to reduce greenhouse gas emissions and to combat climate change effects.

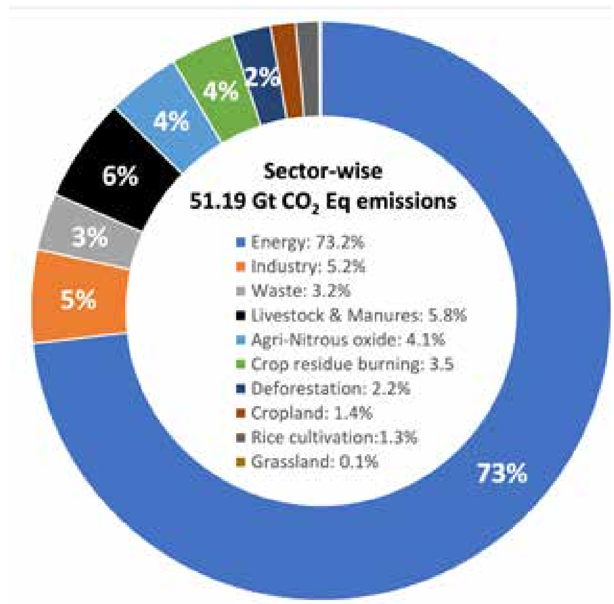

Figure-2 Sector-wise global greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (IPCC, 2021)

2) IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

3) IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

4) https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/

Anthropogenic Emissions

Human activities (anthropogenic) — such as mining and refining fossil fuels, generation of heat and electricity, deforestation, crop production practices, manufacturing of goods, building infrastructure and transportation — are mainly responsible for the rise in GHG emissions. Electricity and heat production contribute 25% to GHG emissions; agriculture, forestry and land use contribute to 24%; Industrial processes contribute to 21%; transportation contributes to 14%; buildings and infrastructure contributes 6.4% and other activities such as mining and refineries contribute to rest of the emissions[5].

Different activities release different gases. The global warming potential (GWP) of each gas is different[6]. Global warming potential is the amount of energy absorbed by one tonne of a gas in 100 years, relative to the emissions of one tonne of CO_2. For example, one tonne of methane absorbs 25 times more energy in 100 years than one tonne of CO_2, which translates to a GWP of 25 for methane. Similarly, nitrous oxide is estimated to have a GWP 298, hydrofluorocarbon-23 with 14,800 GWP, etc[7].

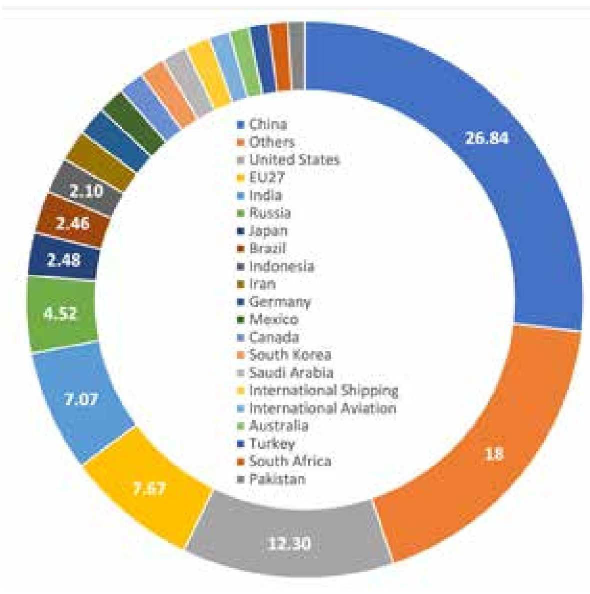

Figure-3 Country-wise global greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (Crippa *et al.*, 2021)

A recent report[8] shows that in 2018, the total GHG emissions were 51.19 giga tonnes (GT = 1 billion metric tonnes); China topped the list of GHG emitters with 13.74 Gt (26.84%) followed by the United States with 6.29 Gt (12.3%); EU27 with 3.93 Gt (2.67%); India with 3.62 Gt (7.7%); Russia with 2.31 Gt (4.52%) and others with 20.03 Gt (23.6%). The report states that 'among these top six world emitters, only China has shown an increase in emissions in 2020 (+1.5%) while all others have decreased their emissions by different amounts: EU27 by 10.6%, United States by 9.9%, Japan by 6.8%, India by 5.9% and Russia by 5.8%.' (Figure 3)

Emissions From Agriculture

Agricultural activities — such as the use of synthetic fertilisers (mainly nitrogenous), manures, lime, crop residue burning, forest burning, deforestation, livestock, enteric fermentation, rice cultivation etc. — emit GHGs. According to the 2021 FAO analytical brief[9], 'In 2018, world total agriculture and related land use emissions reached 9.3 billion tonnes of carbon dioxide equivalent (Gt CO_2eq). Crop and livestock activities within the farm gate generated more than half of this total (5.3 Gt CO_2eq), with land use and land use change activities responsible for nearly 4.0 Gt CO_2eq; these components were 4.6 and 5.0 Gt CO_2eq respectively in the year 2000'.

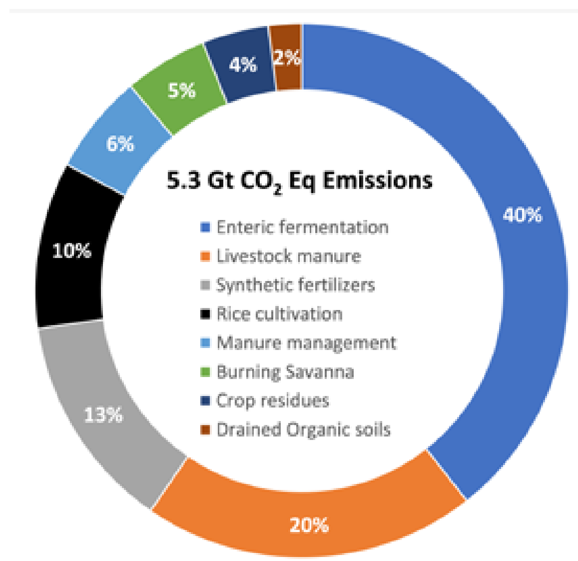

Figure-4. Agricultural sector: greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (FAO, 2021)

5) IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
6) https://www.epa.gov/ghgemissions/understanding-global-warming-potentials
7) https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-chapter-executive-summary.pdf?VersionId=zIDuKzdiajVlVgYiiK_CGXhk36JU02zr
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9) https://www.fao.org/3/cb3808en/cb3808en.pdf

The Cotton Carbon Footprint

Cotton production systems deploy many agricultural technologies that lead to GHG emissions. Inputs such as irrigation water, fertilisers, pesticides, labour, machinery and energy, significantly impact the environment in many different ways thereby influencing sustainability of cotton production and processing. Measuring GHGs, their environmental risks and global warming potential of inputs used in cotton production can help in auditing sustainability and tracking progress. It can also help in sensitising all stakeholders including the actors in the supply chain, mainly consumers.

Agriculture and forest ecosystems play a significant role in capturing CO_2 for photosynthesis and sequestering carbon in soils. An increase in soil organic carbon (SOC) implies that the increased soil carbon mitigates climate change and global warming. Cotton production systems emit GHGs but soils and crops also act as carbon sinks to an extent that in some situations, a cotton crop may have sequestered more CO_2 than the GHG equivalents that it may have emitted. In stark contrast to natural fibres that absorb atmospheric CO_2, the manufacturing process of synthetic manmade fibres, such as polyester and nylon, emits 3-5 times more GHGs compared to cotton[10]. These fibres are prepared from fossil fuels by burning carbon; they neither sequester carbon nor are biodegradable. Cotton and other natural fibres biodegrade in the soil. Although the process of biological degradation leads to CO_2 emissions, it also supports the growth and proliferation of soil microbial organisms, insects and earthworms to enrich soil organic matter through soil carbon sequestration.

The net anthropogenic flux (human activities) has been estimated to emit 9.0 Gt of CO_2 equivalent GHGs every year[11]. Different crop-production systems emit different levels of GHGs. Research showed that the GHG emissions from cotton farms were 2.37 tonnes of carbon dioxide equivalents (CO_2eq) per tonne of lint produced in Pakistan[12] and 1.60 tonnes CO_2eq per tonne lint produced and delivered to port in Australia[13]. Research studies from Iran[14] showed that 1.47 tonnes of CO_2eq GHGs were emitted per tonne of lint produced. Based on studies conducted in China, India, Pakistan, Tajikistan and Turkey, a recent corporate report[15] found that cotton 'production had average annual GHG emissions of 2.93 tonnes carbon dioxide equivalents per tonne lint produced'. Cotton Incorporated estimates GHG emissions in conventional US cotton production at about 1.7 tonnes of CO_2eq per tonne of fibre[16]. From the above reports, the average global emissions may be estimated to be 38.2 (1.47 x 26 Mt) to 76.2 (2.93 x 26 Mt) tonnes CO_2eq GHGs per tonne of cotton lint produced, at an average of 57.2 million tonnes of CO_2eq GHG emissions annually. A study[17] estimates that over 706 million tonnes of CO_2eq of GHGs can be attributed to polyester production (48 million tonnes) for use in textiles in 2015, which may now have increased to an emission of 838 million tonnes of CO_2eq GHGs from 57.1 million tonnes of polyester production.

While many tools calculate only GHG emissions from production systems, there are very few tools that calculate the net carbon balance after factoring the 'CO_2-capturing' capabilities of crops and 'carbon sequestering' potential of soils. Measurement of carbon sequestration rates has not been easy because of the uncertainties imposed by the radically different soil types and cotton production systems across the world. The uncertainties related to carbon sequestration rates may have discouraged the consideration of soil carbon sequestration into the LCA equations. After all, it may be possible that if the full 'carbon-sequestration' potential of cotton crop is estimated and factored into LCA equations, cotton's contribution to the carbon equation may be net negative in some conventional low-input-use production systems, especially if practices such as crop residue recycling, cover cropping and conservation tillage are followed.

Cotton production systems emit CO_2 and other GHGs, but cotton plants also absorb CO_2. Cotton plants utilise atmospheric CO_2 to produce cotton fibre, seeds and biomass. For each unit of fibre produced, the plant produces about 1.5 units of seeds. For each unit of seed-cotton produced, the plant produces about 1.2 to 1.4 units of biomass, which is comprised of stalks and leaves. Cotton fibre contains 94% cellulose[18] and cellulose contains 44.4% carbon[19]. Cotton seeds are comprised of about 50% carbon[20]. Cotton stalks contain 47.05% carbon[21]. CO_2 contains 27.7% carbon; therefore, one unit of sequestered carbon

10) Moazzem, S., Crossin, E., Daver, F., & Wang, L. (2018). Baseline Scenario of Carbon Footprint of Polyester T-Shirt. Journal of Fiber Bioengineering and Informatics, 11(1), 1–14.

11) DOE, (2008). Carbon Cycling and Biosequestration: Integrating Biology and Climate Through Systems Science. U.S. Department of Energy Office of Science. Available online at: http://genomicsgtl.energy.gov/carboncycle/

12) Imran, M., Özçatalbaş, O. and Bashir, M.K., 2020. Estimation of energy efficiency and greenhouse gas emission of cotton crop in South Punjab, Pakistan. Journal of the Saudi Society of Agricultural Sciences, 19(3), pp.216-224.

14) Hedayati, M., Brock, P.M., Nachimuthu, G. and Schwenke, G., 2019. Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: an Australian perspective. Journal of Cleaner Production, 212, pp.974-985.

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16) https://bettercotton.org/better-cotton-releases-our-first-study-on-ghg-emissions/

17) Cotton LEADS – Sustainable Cotton Production. (2019). Cotton carbon FOOTPRINT U.S. https://cottonleads.org/sustainable-production/carbon-footprint-united-states/.

18) Kirchain, R., Olivetti, E., Reed Miller, T. & Greene, S. Sustainable Apparel Materials (Materials Systems Laboratory, 2015).

19) https://textilelearner.net/chemical-composition-of-cotton-fiber/

20) Andreas Bengtsson et al., 2020. Carbon Fibers from Lignin–Cellulose Precursors: Effect of Carbonization Conditions. ACS Sustainable Chem. Eng. 2020, 8, 17, 6826–6833

21) Bellaloui, N., Stetina, S.R. and Turley, R.B., 2015. Cottonseed protein, oil, and mineral status in near-isogenic Gossypium hirsutum cotton lines expressing fuzzy/linted and fuzzless/linted seed phenotypes under field conditions. Frontiers in Plant Science, 6, p.137.

is equivalent to 3.67 units of CO_2. The roots constitute 23.2% of the whole plant biomass[6]. A hypothetical calculation (Table 1) shows that cotton plants could be capturing at least about 366 million tonnes of CO_2 annually to produce 26.0 million tonnes of cotton fibre. Thus, cotton crops capture atmospheric CO_2 and store it in their biomass and the soil. However, the crop biomass degrades eventually to release part of the CO_2 back into the atmosphere. Net carbon sequestration by crops at the field level can be difficult to measure. However, there are estimates of carbon sequestration in oceans, terrestrial life and agricultural ecosystems.

Table-1. Hypothetical estimates (million Mt) of CO_2 absorbed by cotton plants to produce 26.0 million tonnes of fibre.

	Biomass Mt	Carbon content %	Carbon mass Mt	CO_2 Mt
Fibre	26.00	0.44	11.44	41.95
Seeds	39.00	0.5	19.50	71.50
Stalks	97.50	0.47	45.83	168.04
Roots	49.00	0.47	23.03	84.44
Total	211.50	0.47	99.80	365.93

The atmospheric carbon pool is estimated to be 760 GT, while the soil organic carbon pool is estimated to be 2,500 GT, of which 1,500 GT carbon is concentrated in the top 1 metre[22]. Research conducted at the Salk institute[23] shows that 'the planet breathes in (absorbs) around 746 GT of carbon dioxide each year through photosynthesis and other mechanisms. It breathes out 727 GT each year when plants decompose', which means an annual net sequestration of 19 GT CO_2, thus accounting for 2.5% of carbon sequestration. Plant biomass incorporates 123 GT of CO_2 annually through photosynthesis, with terrestrial ecosystems operating as net carbon sinks by sequestering 3 Gt of carbon[24] of which agricultural ecosystems that occupy 5 billion hectares[25] sequester 1 GT of carbon every year[26], which translates to an annual sequestration potential of 0.2 tonnes (200 kg) of carbon per hectare.

Thus — presuming that on an average, 200 kg of organic carbon from plants is finally stored in a hectare of soil — the cotton crop biomass may be retaining a net residual balance of about 6.6 million tonnes of carbon every year by capturing 24.2 million tonnes of CO_2 in 33 million hectares. However, a fact that is very commonly ignored is that cotton fibres are excellent carbon sinks. The 26 million tonnes of cotton fibre produced every year retain 11.44 million tonnes of carbon captured from 41.95 million tonnes of atmospheric CO_2. Though eventually all cotton products biodegrade, a study[27] shows that the carbon storage potential or carbon sequestration factor of cotton is 0.019, which could mean a net sequestration of at least 1.9% carbon from the total solid biomass of the product. Thus, if we presume that all the cotton fibre produced is buried every year, 0.49 million tonnes of carbon would be stored annually from 26 million tonnes of cotton fibre degraded in the soil, which would translate to 1.81 million tonnes of net CO_2 sequestered from the atmosphere. Thus, every year, about 26 million tonnes (24.2 Mt + 1.81 Mt) of CO_2 may be sequestered by the cotton crop and its fibres.

However, carbon sequestration can be enhanced several-fold through technologies such as anaerobic pyrolysis of the organic biomass. Cotton fibre and cotton stalks can be subjected to anaerobic pyrolysis to be easily converted to carbon-rich biochar or hydrochar, which can be incorporated back into the soil to enrich it with organic carbon. Studies[28] showed that the 26% to 38% of carbon was sequestered in biochar prepared from cotton stalks. Therefore, if it is assumed that an average of 32% carbon can be stored in biochar, cotton stalks alone — if converted to biochar — will have the potential to sequester 53.76 million tonnes of CO_2. Thus, if stalks and fibres are effectively deployed as carbon sinks, even conventional cotton production systems that are estimated to emit an average of 57.2 million tonnes of CO_2 equivalent GHGs annually will easily turn out to be carbon negative or climate positive.

A recent report[29] highlights the potential of cotton crop biomass in capturing CO_2 to show that 'an acre of no-till cotton actually stores 150 kg more of atmospheric carbon than it emits during cotton production, meaning that cotton's contribution to the carbon equation is net negative'. Thus, no-till cotton farming, if adopted globally, has the potential to sequester an estimated 12.2 million tonnes of extra carbon which is equivalent to the removal of 44.1 million tonnes of CO_2 in excess of what the crop emits during production. LCA studies[30] indicate

22) Al Afif, R., Pfeifer, C. and Pröll, T., 2019. Bioenergy recovery from cotton stalk. Advances in cotton research.

23 https://www.salk.edu/harnessing-plants-initiative/research/

24) Le Quere, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., et al. (2018). Global carbon budget 2018. Earth Syst. Sci. Data 10, 2141–2194. doi: 10.5194/essd-10-2141-2018

25) https://www.fao.org/sustainability/news/detail/en/c/1274219/

26) Jansson, C., Faiola, C., Wingler, A., Zhu, X.G., Kravchenko, A., de Graaff, M.A., Ogden, A.J., Handakumbura, P.P., Werner, C. and Beckles, D.M., 2021. Crops for Carbon Farming. Frontiers in Plant Science, 12, p.938.

27) Zheng, W., Phoungthong, K., Lü, F., Shao, L.M. and He, P.J., 2013. Evaluation of a classification method for biodegradable solid wastes using anaerobic degradation parameters. Waste management, 33(12), pp.2632-2640.

28) Venkatesh et al., 2014. Biochar Production Technology for Conversion of Cotton Stalk Bioresidue into Biochar and its Characterization for Soil Amendment Qualities. Indian J. Dryland Agric. Res. & Dev. 2013 28(1) : 48-57

29) Cotton LEADS – Sustainable Cotton Production. (2019). Cotton carbon FOOTPRINT U.S. https://cottonleads.org/sustainable-production/carbon-footprint-united-states/

30) Cotton Incorporated (2009). Summary of Life Cycle Inventory Data for Cotton (Field to Bale – version 1.1 – 2 July 2009). Cotton Incorporated, United States of America, 31 p.

that the cotton crop is climate positive and removes additional carbon dioxide from the atmosphere than the CO_2 equivalent greenhouse gases (GHGs) it emits. The studies[13] show that cotton production could be considered a 'carbon sink', since the amount of carbon stored in the fibre (42%-44% carbon) and soil could be higher than the total GHG emitted into the atmosphere during cotton production and ginning. According to the report[13], 'If credit were given for the amount of biodiesel that could be produced from the cottonseed oil and if the carbon emissions from petroleum diesel were replaced with biodiesel (~0.6 kg CO_2eq per kg of fibre), then cotton production from the field to the bale would have higher stored GHGs than portrayed'.

Cotton's Adaptability To High CO_2 Levels

Cotton plants are sensitive to high temperatures but have additional abilities to capture CO_2. Cotton is a C3 plant —like rice, wheat and soybeans — which is different from a C4 plant (maize, sugarcane and sorghum) because the first stable intermediate in photosynthesis is the 3-carbon compound called phosphoglyceric acid, whereas in C4 plants, it is the 4-carbon compound called oxaloacetic acid. CO_2 fixation occurs only once in C3 plants and twice in C4 plants and CO_2 fixation is slower in C3 plants than in C4 plants. Nevertheless, C3 plants are more specifically endowed with physiological capabilities to exploit higher levels of CO_2 in the atmosphere. The global CO_2 levels are increasing every year beyond 400ppm. Interestingly, 'cotton, as a C3 plant, continues to benefit from enhanced CO_2 levels up to 800 ppm, compared to C4 plants that do not benefit from enhanced CO_2 levels beyond 420ppm[31]'. Saturating CO_2 was found to increase both photosynthetic nitrogen-use-efficiency (PNUE) and photosynthetic water-use-efficiency (PWUE) in C3 plants[32]. There is no doubt that evolutionarily, C4 plants can cope with higher temperatures, less water and available nitrogen, and have a better photosynthetic capacity compared to C3 plants, with a better PNUE and PWUE in C4 plants compared to C3 plants[33]. However, at low temperatures, C3 plants were found to have a better PNUE and PWUE[34]. Moreover, the advantages of C4 plants over C3 plants have been reported to eventually disappear under nitrogen and water stress[35], probably due to CO_2 leakage[36]. Thus, cotton plants not only have the additional advantage of sequestering carbon in its fibre but also possessing capabilities of utilising higher CO_2 levels to combat climate change.

Pesticides and Soil Health

Cotton is known to host a large number of insects and micro-organisms, some of which harm the crop but most protect the crop from harmful pests. Ecology is comprised of a biodiversity of flora and fauna that functions in a natural equilibrium in the absence of unnatural disrupting factors. Human interventions such as deforestation, the introduction of susceptible crop varieties, improper agronomic practices, imbalanced use of fertilisers and the indiscriminate use of broad-spectrum pesticides cause disruption of ecosystems thereby leading to loss of biodiversity, increased pestilence and outbreaks. Historically, cotton farming has been subjected to intensive pesticide applications in many parts of the world. Most pesticides show acute or chronic toxicity to earthworms and soil microorganisms[37]. Pesticides can degrade soil health. Pesticides kill soil-dwelling insects, earthworms and strongly disrupt soil microbial ecosystems to reduce biodegradation rates and their carbon sequestration capabilities. Poor soil health leads to poor crop growth, low CO_2 capture, low yields and poor carbon sequestration.

Textile Emissions And Pollution

It is estimated[38] that the manufacturing process of 1 kg fabric emits 20-23 kg CO_2eq GHGs. The fashion industry is responsible for about 2.10 Gt of CO_2eq GHG emissions[39] through material production (38%), wet processing (15%), yarn manufacture (8%), fabric preparation (6%), cut and trim (4%), product use (20%) and 3% each from retail, transport and end-use of the product. Different textile processes have different amounts of electricity and energy. In textile processing, the share of electricity usage is 41% for spinning, 19% for humidification, 13% for weaving, 5% for weaving preparatory processes, 10% for wet processing and 12% for other processes. Electricity in spinning processes is mostly used by ring spinning machines (37%), open end machines (20%), carding (12%), blow room (11%), 7% each for simplex and winding machines, 5% by drawing machines and 1% for combing[40].

31) Raja Reddy, K. 2020. Climate Change and Cotton. WCRC-7 Webinar, 4 November 2020. https://www.youtube.com/watch?v=c1JKVHW00OI
32) Wand S.J.E., Midgley G.F., Jones M.H. and Curtis P.S. (1999) Responses of wild C3 and C4 grasses (Poaceae) to elevated atmospheric CO2 concentration: a meta-analytic test of current theories and perceptions. Climate Change Biology 5, 723-741.
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38) https://climatescience.org/advanced-fashion-textiles-sustainable
39) https://www.mckinsey.com/~/media/mckinsey/industries/retail/our%20insights/fashion%20on%20climate/fashion-on-climate-full-report.pdf
40) Rana, S., Pichandi, S., Karunamoorthy, S., Bhattacharyya, A., Parveen, S. and Fangueiro, R., 2015. 7 Carbon Footprint of Textile. Handbook of sustainable apparel production, p.141.

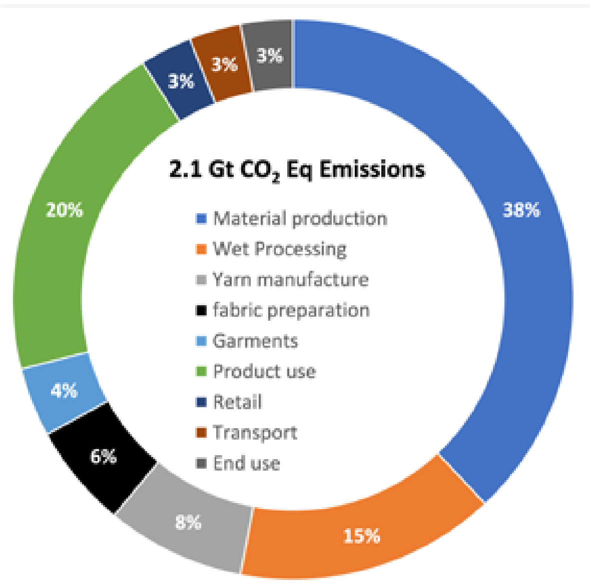

Figure-5 Textile sector: greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (Mckinsey.com Ref:39)

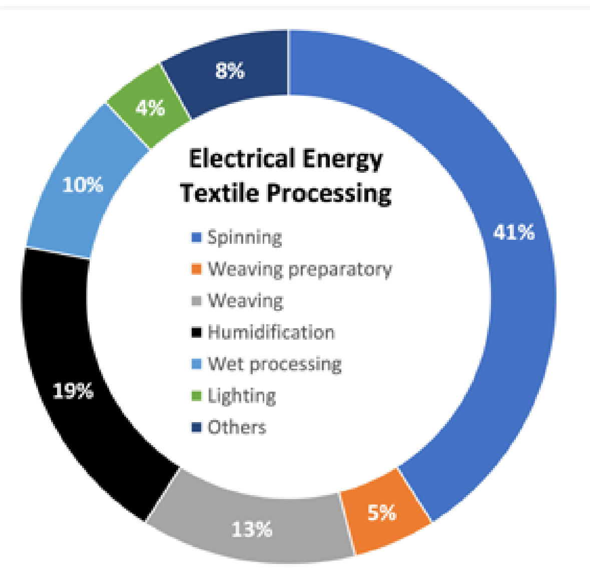

Figure-6 Electrical energy (%) consumed in textile processing (Jain, 2017)

Wet processing of textiles involves washing, desizing, mercerizing, dyeing, printing, etc. and it require about 2,000 different chemicals[41]. 'A single mill can use 200 tons of water for each ton of fabric it dyes. And rivers run red--or chartreuse, or teal, depending on what color is in fashion that season--with untreated toxic dyes washing off from mills'.[42] Water is used for dissolving chemicals, washing, rinsing, etc., eventually polluting water streams. The author's calculations (based on ref: 38) show that 18 KWh of electricity, which is generated by burning 2.2 kg of coal, is required to produce 1 kg of fabric.

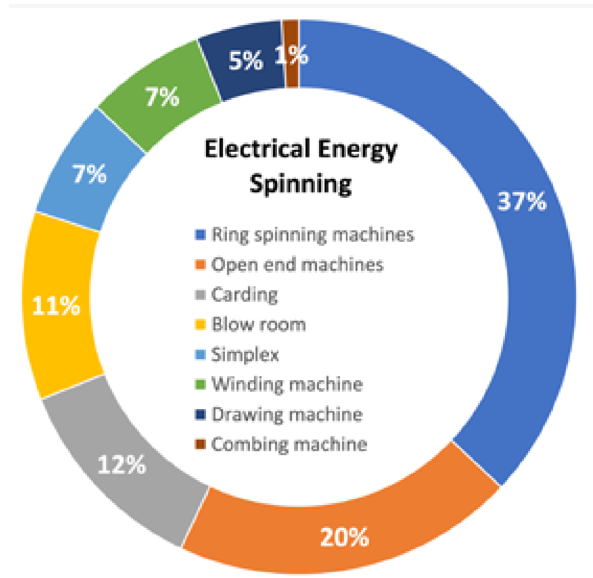

Figure-7 Electrical energy (%) consumed for processes involved in spinning (Jain, 2017)

Crop Production Mitigation Strategies

From an agricultural standpoint, greenhouse gases such as CO_2, N_2O and CH_4 are emitted due to anthropogenic activities and carbon dioxide is absorbed by plants, animals and microorganisms. Farming systems emit CO_2 and other GHGs, but agricultural crops that are an integral part of farming systems have great potential to absorb huge quantities of atmospheric CO_2 to eventually store carbon in the soil. Soils that are rich in carbon benefit planetary health in many ways. They not only function as long-term carbon-repositories to mitigate global warming, they also foster good soil health for higher productivity of food, feed and fibre. Soil organic carbon (SOC) facilitates better nutrient uptake, enhances nutrient-use efficiency and improves water-use efficiency. Sustainable cotton farms deploy agronomic technologies that result in healthy soils, clean water and healthier farm ecosystems, thereby enhancing environmental and social sustainability. Sustainable textile systems are expected to deploy eco-friendly technologies to reduce GHG emissions and minimise pollution.

There are several excellent documents highlighting agricultural technologies that help to decrease GHG emissions and increase carbon sequestration. This section provides only a brief list of strategies limited to cotton-based cropping systems with focus on enriching soil organic carbon (SOC).

Soil Health

Soil heath determines plant health. Rejuvenating soil health holds the key to sustainable farming. When soil health improves, it leaves a visible fingerprint on crop productivity, biodiversity and ecosystems. Soils that are rich in organic matter help crops capture more CO_2 and are better equipped for carbon

41) Jain. 2017. Ecological approach to reduce carbon footprint of textile industry. International Journal of Applied Home Science. 4: 623-633
42) NRDC (2011) "Green Fashion: Beautiful on the Inside." Smarter Living

sequestration. Good soil health is most important for sustainable farming. Soil health is influenced by its organic matter, soil carbon, soil fertility, soil bulk density and soil microbiota. Enriching soils with organic matter is done by adding organic biomass and through conservation agricultural practices. Some of the most important technologies to rejuvenate soil health are:

- Recycling crop residues
- Use of cover crops
- Conservation agricultural practices such as minimum tillage
- Use of green manure
- Application of manures and compost
- Use of bio-fertilisers
- Use of biochar or hydrochar
- Avoidance of soil pollutants

Cover crops and minimum tillage have been playing a significant role in improving soil health in many countries across the world. Roots of cover crops provide a robust matrix in the top surface of the soil to reduce soil erosion and degradation. Legume cover crops enrich the soil with nitrogen and enhance productivity and promote soil health. A proper choice of cover crop or mixtures of crops can help reduce GHG emissions. A recent study[43] showed that residues from an oat cover crop retained higher soil moisture compared to winter peas and mustard residues. The study also showed that degradation of a mix species of cover crops emitted higher levels of CO_2, N_2O and CH_3 compared to individual cover crops. Crop residue recycling, reduced tillage and no-till systems enable soil conservation and enhance carbon sequestration to enrich soil organic matter.

Carbon Farming

Carbon farming aims to increase carbon reserves by enriching soils with organic matter, microbial biomass and enhancing photosynthetic capabilities of improved varieties selected for better CO_2 capture and higher productivity. Soil carbon reserves can be enriched through carbon farming[20] which encompasses principles of regenerative agriculture, enriching soil microbial consortia and breeding crops that possess high carbon sequestration capabilities. Microbial biomass is enriched by inoculating the soils with designated microbial consortia that degrade organic biomass efficiently with highest carbon sequestration potential coupled with low CO_2 respiration. Plant breeding and genetic techniques can lead to the development of crop varieties that are climate-resilient, heat-tolerant and have enhanced photosynthetic capabilities to capture higher levels of CO_2, thereby leading to higher productivity.

Nutrient Management

Cotton production requires the optimised use of nutrients. Of all agrochemicals, 'nitrogenous fertiliser use' is known have the largest carbon footprint and is the biggest contributor to greenhouse gas emissions (GHGs) apart from causing eutrophication (which occurs when fertiliser runoff causes dense plant and algal growth in water bodies that results in the death of animal life from lack of oxygen). Many agrochemicals including most pesticides pollute the soil and affect soil microorganisms, earthworms and insects that play a significant role in soil health, but nitrogenous fertilizers are the main sources of N_2O and NH_3. Precision technologies of nitrogen application timing and rates based on soil analysis to match the crop requirements will enable better nitrogen-use-efficiency. The use of enzyme inhibitors to delay nitrogen release helps to minimise nutrient losses and N_2O emissions.

Agrochemical Management

Synthetic pesticides are produced from fossil fuels. Most pesticides disrupt the natural ecosystems and harm earthworms, beneficial insects and soil microbes. There are more than 2,395 generic pesticides (comprising mostly of insecticides, herbicides, fungicides) and 582 generic insecticide molecules that have been registered in more than 50,000 different formulations across the globe. The Pesticide Action Network (PAN) has identified 310 highly hazardous pesticides (HHPs). Amongst all the factors that influence environmental sustainability of agriculture, chemical pesticides have the greatest negative impact. According to WHO data[44], in 2012, an estimated 193,460 people died worldwide from unintentional poisoning. While it is known that most pesticides are toxic to insects, plants, humans and many other forms of living organisms including soil microorganisms, there are no specific estimates on the extent of harm that pesticides may have caused to soil microorganisms and soil health. However, there are also a few eco-friendly pesticides that cause minimum disruption to the soil fauna thereby enabling uninterrupted biodegradation and carbon sequestration. There is a need to shortlist and deploy eco-friendly pesticides that have selective toxicity to target pests but cause least harm to non-target organisms and soil microorganisms.

Policies and Responsibilities

Governments can play a greater role in enacting and implementing policies that reward carbon farming to have a larger impact on reducing GHG emissions, encouraging afforestation and enhancing carbon sequestration. Scientists must develop technologies to reduce GHG emissions and increase carbon storage in cotton farms and strategies to adapt, minimize, mitigate and combat the impacts of climate change. Farmers have a responsibility to make farming systems sustainable, eco-friendly and carbon-positive.

Textile Mitigation Strategies

Increase the use of natural fibres

Synthetic fibres are produced by burning fossil fuels and do not assist the environment in any way. Agriculture, on the

43) Salehin, S.M.U., Rajan, N., Mowrer, J., Bagavathiannan, M., Casey, K. and Tomlinson, P., Greenhouse gas emissions, soil moisture and temperature dynamics with different cover crops in organic cotton. 2021 Beltwide Cotton Conferences, Virtual, January 5-7, 2021. 208-213

44) WHO, ILO and UNEP. International program on chemical safety, poisoning prevention and management report 2012 Geneva, Switzerland WHO http://www.who.int/pcs

other hand, has immense potential to absorb carbon dioxide from the environment. Synthetic fibres cause environmental pollution through micro-plastic accumulation and poor degradation. Natural fibres are produced from agriculture which can be efficiently transformed into an effective carbon sink through regenerative agricultural practices. Promoting the use of natural fibres holds promise for carbon sequestration and mitigation of climate change.

Reuse and recycle

It is estimated that 1.17 million tonnes of textiles are discarded every year[38]. Reusing clothes to extend their life without substituting them with synthetic fabrics will go a long way toward reducing carbon emissions.

A study showed that 'extending the lifespans for 10% of t-shirts in the market would reduce circa 100,000 tonnes of CO_2eq GHGs and 2000 tonnes of waste per annum in the UK alone[45]. Studies show that the recycled clothing system reduces energy consumption by 84% and CO_2 emissions by 77%[38]. Industries must explore business avenues for reuse and recycling textiles with minimal disruption to ecology and the environment.

Adopt eco-friendly technologies in wet processing

Several eco-friendly technologies have been identified for wet processing. Notable amongst these are enzymatic processing, radiofrequency, electrochemical dyeing, microwaves and infrared heating. A few prominent eco-friendly technologies are listed below:

1. **Bleaching and oxidising:** Substitution of sodium silicate with organic stabilisers such as polyhydroxy carboxylic acid and their ammonium salts and polyacrylic acids to be used with hydrogen peroxide in bleaching and oxidising[38]. Single-step, ultrasonic-assisted redox bleaching and use or radio waves and ultrasonic waves with low-temperature dyeing reduces pollution and saves both energy and time[46].
2. **De-sizing and scouring:** Enzymatic de-sizing with amylases and lipases; enzymatic bio-scoring with pectinases, proteases and lipases; and solvent-assisted scouring and bleaching with potassium permanganate, glucose oxidase, pectinase and amino-glucosidases eliminates the need for harmful synthetic chemicals[47].
3. **Dyeing and printing:** Liquid carbon dioxide in super critical fluid dyeing reduces heavy metal and aqueous effluents[48]. The adoption of air technology, fibre-reactive eco-friendly dyes and low-impact natural dyes has the potential to replace azo and phthalate dyes in printing. Ink-jet printing and digital printing eliminates toxic chemical processing. Formaldehyde-free pigment printing systems and acrylic-based inks in screen printing reduce pollution significantly[38].
4. **Finishing:** Non-formaldehyde-containing resins such as dimethyl-dihydroxy-ethylene-urea, citric acid or butane tetra carboxylic acid can be used for eco-friendly finishing[49]. 'Colour-fast-finish' technology for finishing has the potential to reduce CO_2 emissions[38].

Conclusions

Like any crop, cotton production emits GHGs and causes climate change and global warming. Climate change causes elevated CO_2, higher temperatures and disruptions in rain patterns, all of which are known to seriously influence cotton production. However, agricultural systems absorb CO_2 and sequester significant amounts of carbon to reduce global warming. Cotton plants utilise CO_2 and thus reduce greenhouse gas effects. With sustainable practices, a cotton production system can sequester more carbon than the CO_2 equivalent greenhouse gases that it emits. Amongst crops, cotton is unique because it stores carbon in its cellulosic fibres which are not rapidly perishable, unlike many food products. Cotton fibres are processed for value addition and the textile processing emits GHGs. Textile products, when discarded, biodegrade in landfills thereby serving as a food source for soil microorganisms to result in GHG emissions and carbon sequestration. Cotton is a natural fibre that degrades rapidly compared to the non-degradable synthetic fibres that are made from non-renewable fossil fuels. Moreover, synthetic fibres break down into micro-plastics and pollute rivers and oceans. Sustainable production and processing of cotton involves implementing strategies that strive to minimise the carbon footprint, minimise greenhouse gas (GHG) emissions, sequester carbon and reduce its footprint. Sustainable technologies aim to optimise energy and water usage; avoid the use of highly hazardous pesticides and chemicals; avoid polluting the air, soil and water; conserve biodiversity; enhance nitrogen-use-efficiency; rejuvenate soil health; enhance productivity; ensure fair trade; increase profitability and reduce poverty; safeguard animal welfare; ensure gender and child equity; prohibit labour exploitation; and foster social well-being. A number of strategies are available that can be deployed to reduce GHG emissions in fibre production and processing and to enhance carbon capture and carbon storage in crop production systems and to mitigate the effects of climate change on cotton production. Climate change effects can be mitigated through sustainable cotton farming, processing and sustainable use of fabrics. Strategies to mitigate greenhouse gas emissions in the production and supply chains include optimised use of nitrogenous fertilisers, electricity, water, energy and avoidance of highly hazardous chemicals in farms and

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48) Malik, S.K. and Kaur, H. (2005). Supercritical carbon dioxide - The dyeing technique of future. Man Made Textiles India. 48 (1) : 27-32

49) Gulrajani, M.L. and Gupta, D. (2011). Emerging techniques for functional finishing of textiles. Indian J. Fibre & Textile Res., 36 (4): 388-397

factories. Research must be focused to develop eco-friendly 'alternative technologies' — with reduced dependence on fossil fuels — that minimise GHG emissions.

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