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].

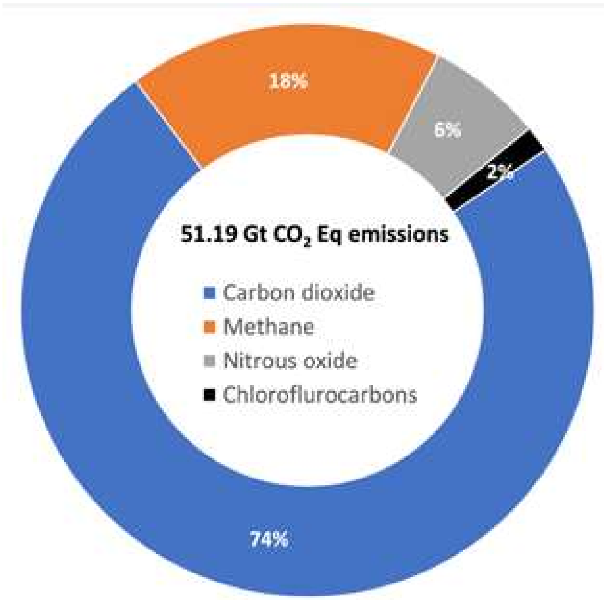

Figure-1 Global greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes in 2018 (Data Source World Bank)

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.

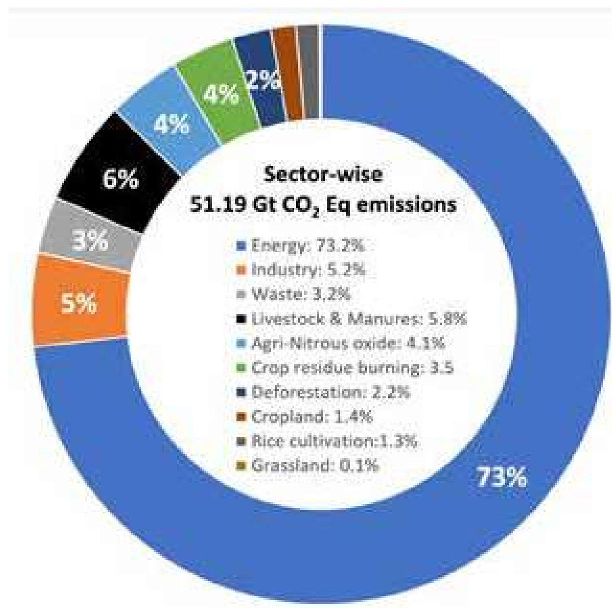

Figure-2 Sector-wise global greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (IPCC, 2021)

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].

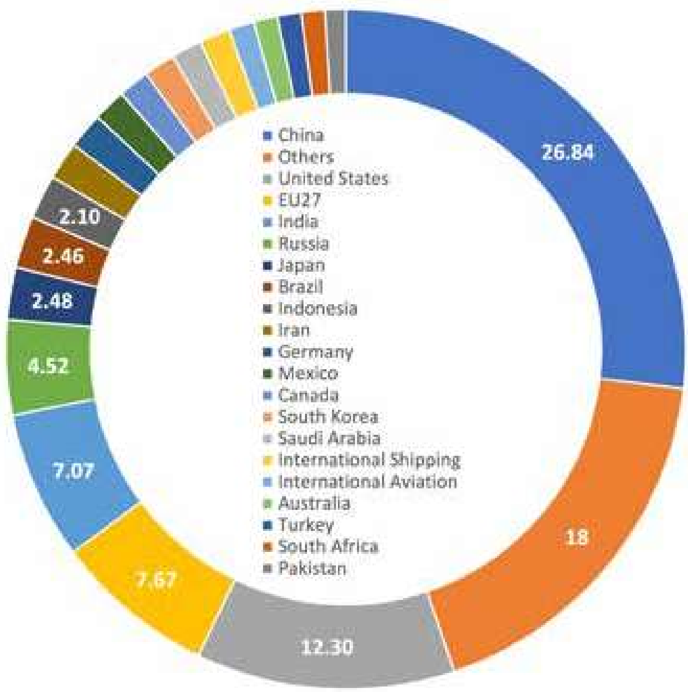

Figure-3 Country-wise global greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (Crippa et al., 2021)

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'.

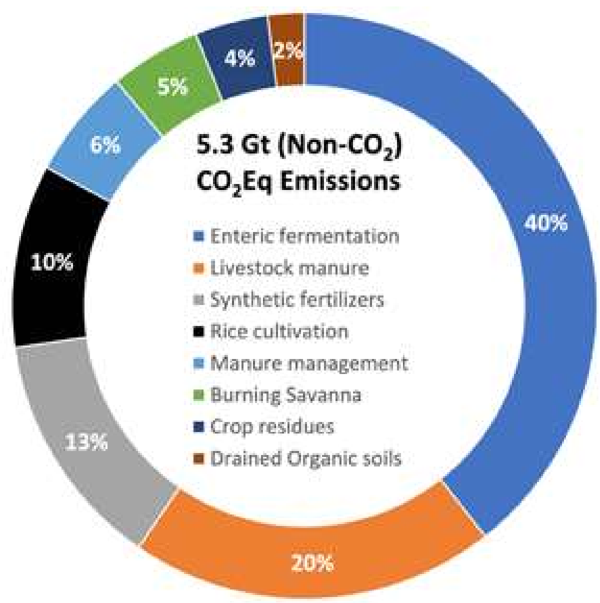

Figure-4. Agricultural sector: greenhouse gas (GHG) emissions in non-CO_2 carbon dioxide equivalents (CO_2eq) Giga Tonnes (FAO, 2021)

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

8) Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J.G.J., Grassi, G., Rossi, S., Vignati, E.,GHG emissions of all world countries - 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, doi:10.2760/173513, JRC126363

9) https://www.fao.org/3/cb3808en/cb3808en.pdf

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 CO2eq 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 GH 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.

13) 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.

14) Sami, M. and Reyhani, H., 2018. Energy and greenhouse gases balances of cotton farming in Iran: a case study. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 66(1), pp.101-109.

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

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

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

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

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

20) 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.

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

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	26.0	0.44	11.44	41.95
Seeds	39.0	0.50	19.50	71.50
Stalks	97.5	0.47	45.83	168.04
Roots	49.0	0.47	23.03	84.44
Total	**211.5**	**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) Jansson, C., Wullschleger, S. D., Udaya, C. K., and Tuskan, G. A. (2010). Phyto-sequestration: carbon bio-sequestration by plants and the prospects of genetic engineering. Bioscience 60, 685–696. doi: 10.1525/bio.2010.60.9.6
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 microorganisms, 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.

33) Taylor S.H., Hulme S.P., Rees M.E., Ripley B.S., Woodward F. I. and Osborne C.P. (2009) Ecophysiological traits in C3 and C4 grasses: a phylogenetically controlled screening experiment. New Phytologist 185, 780-791.

34) Schmitt M.R. and Edwards G.E. (1981) Photosynthetic capacity and nitrogen use efficiency of maize, wheat and rice: a comparison between C3 and C4 photosynthesis. Journal of Experimental Botany 32, 459-466

35) Ghannoum O. (2009) C-4 photosynthesis and water stress. Annals of Botany 103, 635-644.

36) Buchmann N., Brooks J.R., Rapp K.D. and Ehleringer J.R. (1996) Carbon isotope composition of C4 grasses is influenced by light and water supply. Plant, Cell and Environment 19, 392-402

37) Nannipieri, P.; Ascher, J.; Ceccherini, M.; Landi, L.; Pietramellara, G.; Renella, G. Microbial diversity and soil functions. Eur. J. Soil Sci. 2003, 54, 655–670

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.

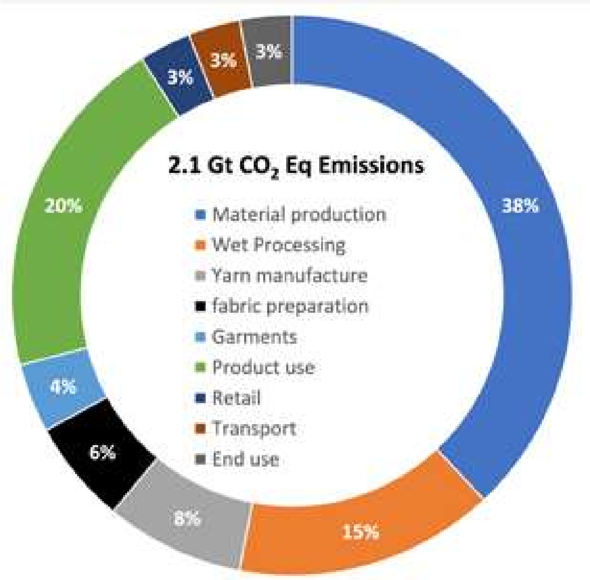

Figure-5 Textile sector: greenhouse gas (GHG) emissions in carbon dioxide equivalents (CO_2eq) Giga Tonnes (Mckinsey.com Ref:39)

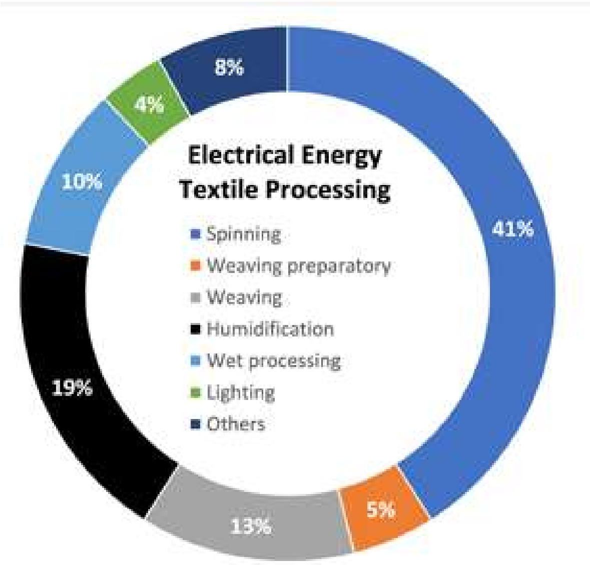

Figure-6 Electrical energy (%) consumed in textile processing (Jain, 2017)

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.

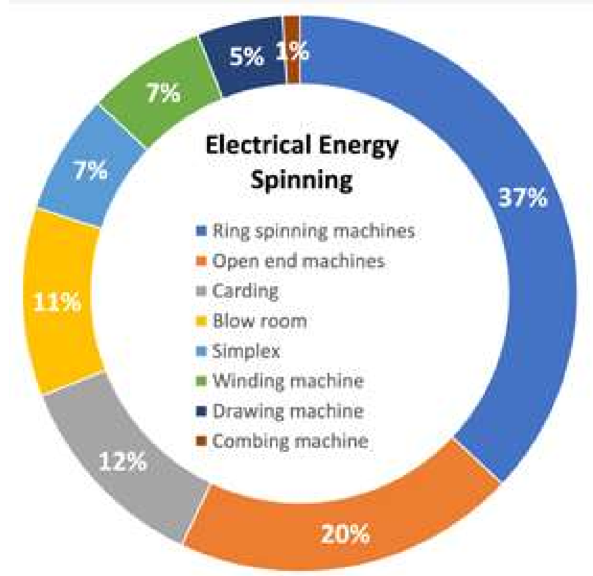

Figure-7 Electrical energy (%) consumed for processes involved in spinning (Jain, 2017)

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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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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