

Spinning Future Threads

The Potential of Agricultural Residues as Textile Fibre Feedstock

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About this Report

This report explores a new avenue for materials innovation in textile manufacturing – harnessing the potential of agricultural waste and residues as an alternative feedstock for producing textile fibres at scale. This cutting-edge innovation offers strong potential to decrease extensive crop burning and its associated negative environmental and climate impacts; generate new, additive low-cost revenue streams for low-income agricultural communities in South and Southeast Asia; and, activate a scalable and more environmentally sustainable source of fibre for the booming apparel and fashion industry.

The report systematically reviews the current state of innovation in technology and processes, and existing economic and market potential to activate major agro-residue hubs in eight countries in South and Southeast Asia – Bangladesh, Cambodia, India, Indonesia, Pakistan, Sri Lanka, Thailand and Vietnam. The authors outline actionable recommendations and chart a roadmap for setting up alternative textile value chains based on specific agro-residues.

Scaling up existing niche innovations could unlock the potential of widely available, yet under-used, natural resources to benefit the global economy and environment. A responsible and environmentally conscious approach to sourcing and utilising agro-residues will be essential for building long-term alternatives to conventional textile value chains. Through this effort, the authors hope to nudge manufacturers, innovators, design experts and global brands to rethink business as usual, and take concrete steps towards building a more sustainable future for the fashion industry.

The ecological and socio-economic sustainability of biomass: Acknowledging the debate

The authors of this report acknowledge the healthy debate surrounding the sustainability of biomass removal and its existing uses, particularly agricultural waste and residues. Valid concerns and questions have been raised about the long-term sustainability of large-scale biomass initiatives, and about their potential adverse environmental and socio-economic impacts – particularly in low-income or rural communities.

The authors understand and share these concerns, and have taken great care in their review, and in this report, to account for and address them. The agro-residues identified herein for further exploration comprise a large, already existing and currently unused or under-used biomass resource base that, properly captured and processed, can be used to generate cellulose-based feedstocks for producing textile fibres. Activating these innovations would not require increasing land under cultivation, or increasing crop volumes, and the authors would not put them forward otherwise.

Additionally, the authors emphasize that in exploring or commercialising these value chain alternatives, the overarching concern must be ensuring that they will not cause negative disruptions in existing socio-economic conditions or ecosystems, particularly rural or agricultural ecosystems. All of the focus countries in South and Southeast Asia included in this study already face unique vulnerabilities, challenges and risks due to rapidly changing environmental and climate conditions. Labour conditions in farming communities in these countries can be challenging, and income stability precarious. The authors have aimed to offer specific pathways that reduce waste, utilise existing resources, and ensure that issues like land use pattern, food security, water security and sustainable agrarian practices are addressed. The authors believe that conscious sourcing decisions can help farmers, farm communities, and the textile industry achieve greater sustainability while ensuring that the delicate balance between people, planet and profits is upheld and safeguarded. The report offers a modest beginning for a steep learning curve.

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Foreword

Fashion's material mix is ripe for disruption - and the emergence of innovations over the last few years is testament to this. From growing fibres in petri dishes, to extracting them from food waste and textile waste; the possibilities are endless. These innovations signal a beacon of hope for an industry that is today so heavily reliant on unsustainable fibres that are harming people and the planet.

Agriculture-residue based fibres are one such class of innovations that holds promise and could potentially speak to dual objectives. One, as a solution to the fashion industry's search for alternatives and in parallel, a pathway for millions of farmers who burn their crop residues and set off dangerous levels of emissions for the want of better options. Innovators have been working to iterate the technical capabilities to suit the fashion industry's requirements. However, the industry's use of them at commercial scale rests on uncovering critical links to feedstock availability, quality, and downstream logistics. The use of agriculture waste as a source for fashion materials is still a niche and it is ever so critical that the system is designed right, from the start as one that is technically fit-for-purpose while also valuing the planet and producers at the core, ensuring that they are not left worse-off in the future.

To this end, Laudes Foundation commissioned this study undertaken by a consortium consisting of the Institute for Sustainable Communities, Wageningen University & Research, and the World Resources Institute to identify agro-residue hubs in South and Southeast Asia, map out the logistics and technical requirements to move unused agro-residues into fashion's fibre mix, and begin to examine the case for producers while outlining any unintended consequences of doing so. The study shows that there is sufficient crop residue that can be channelled to fibre production and underscores the importance of collaborative interventions across the agri-food and fashion systems to enable this at scale. It lays out the initial building blocks for a blueprint to help the industry navigate this transition.

The study provides a stepping stone for innovators to forge ahead on designing pathbreaking solutions, practical guidance for manufacturers to integrate agriculture residues in their supply chains, a roadmap for brands to move from thought to action, and insights to drive participation of civil society and producers to co-create this system.

As Laudes Foundation pushes forward on its journey to foster a just and regenerative materials system, we know that we must purposefully stitch together unlikely alliances to scale truly innovative solutions that recognise the larger issues of climate and inequity. It is only with our collective efforts that we will be able to unlock the necessary investments to transform fashion's material mix. We hope that this research inspires stakeholders to act towards this vision.

Lakshmi Poti
Senior Programme Manager, Materials
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Executive Summary

A booming industry, an unstable resource base, and a call to action

The global textile industry has grown by leaps and bounds, boosted by population growth, a booming global middle class, rising income levels, and the proliferation of fast fashion.

In parallel with this stupendous growth, concerns related to water, energy, chemicals and resource management have come to the forefront, fuelling a drive towards sustainable fashion. Sustainability considerations are being elevated across the entire value chain, from raw materials, to efficiencies of production, transport and use, to closing the loop on recycling and reuse.

The current fibre mix in the textile industry is not sustainable. Synthetics rely on fossil fuels, heavy processing, and intensive chemical use. Recycled fibres – whether from textile waste or alternative regenerative processes – show promise, but so far lasting, long-term solutions remain elusive. Even traditional natural fibres like cotton, linen, hemp, etc. face major challenges. Cotton is the largest textile commodity under cultivation, and conventional cotton relies on intensive water and chemical use, and intensive land use. Major cotton growing areas in Asia and Africa face increasing vulnerability to climate-driven shocks and stresses, and conventional cotton's future sustainability as a textile feedstock is highly uncertain.

Agro-residues: a new and promising part of the solution

An industry-wide hunt for newer, better materials indicates that bio-based alternatives show great promise. As this study shows, regions like South Asia and Southeast Asia, already critical natural fibre producers and textile hubs, generate massive amounts of potentially usable – and currently unused or underused – agricultural waste products, by-products and residues ("agro-residues"). Several areas where agro-residues already coincide geographically with existing or potential processing capacity, present ready-made avenues for directing these residues towards productive uses. Activating this value chain offers great potential to: decrease extensive crop burning and its associated negative environmental and climate impacts; generate new, additive low-cost revenue streams for low-income agricultural communities in South and Southeast Asia; and, activate a new, scalable and more environmentally sustainable source of fibre for the booming apparel and fashion ndustry.

Systematically quantifying the true potential of agro-residues

This report synthesizes the findings, insights and outcomes from comprehensive quantitative and qualitative analyses to assess the physical, technological and economic feasibility, and long-term viability, of agro-residue-based cellulose and fibre value chains. The study focused on existing innovations and technologies for producing agricultural fibres and manmade cellulose fibres (MMCFs) for use in textile manufacturing. A combination of methods, including statistical analysis of secondary databases; GIS mapping; ground validation exercises; and stakeholder consultations; were used to assess the pre-feasibility considerations – including and especially, environmental sustainability – and develop a set of actionable recommendations for implementing and scaling up these alternative value chains.

Eight countries in South and Southeast Asia – Bangladesh, Cambodia, India, Indonesia, Pakistan, Sri Lanka, Thailand and Vietnam – form the geographic scope of the study. These were selected due to their abundant biomass resources (especially agro-residues), large textile manufacturing output, and status as current and future global economic growth centers.

Key study findings and outcomes

The study generated the following key findings and-outcomes:

- **Several existing technological innovations have already demonstrated early promise in producing usable textile fibres from sustainably sourced agro-residues** from agricultural products like banana, citrus, mushrooms, pineapple, etc.

- **Unused or under-used agro-residues are already present in South and Southeast Asia in massive quantities**, including large-scale availability of rice (husk and straw), wheat (husk and straw), empty fruit bunches (EFBs) from oil palm, sugarcane bagasse, and banana plantains.
- **A spatial mapping analysis identified at least ten specific locations in South and Southeast Asia where large-scale availability of existing agro-residues coincides with existing or potential processing capacity,** indicating that hubs for converting agro-residues to textile fibre at scale could be established with a biomass sourcing radius of 100 kms, and in some cases, of just 50 kms.
- **Cost projections vary and require further vetting through pilots, but are favorable.** The lowest cellulose-based biomass extraction-plant gate cost is projected at USD 63 per tonne of cellulose, with the upper end of the range at USD 160 per tonne.
- **Potential socio-economic and environmental consequences of establishing agro-residue value chains appear to be minimal**, and in fact, these value chains appear to offer considerable positive socio-economic and environmental benefits in terms of diversifying agricultural revenues without significant additional investments, and reducing the harmful effects of crop burning and disposal[1].

In short, the findings of this report present a strong foundation for mainstreaming agro-residues in textile fibre and apparel production, and highlight existing opportunities to pursue a deliberate transition strategy. Following the sections that detail the methodologies employed in the study and a discussion of the findings and implications, this report offers a roadmap that highlights existing opportunities and steps that could be taken to pursue a thoughtful and deliberate approach to activating agro-residue value chains, and pave the way for industry and brand pilots to mainstream these new approaches.

1 As noted in "About This Report" above, the authors acknowledge and understand extant concerns about the large-scale use of biomass, and reiterate here their overriding commitment to ensure that any decision to commercialize new approaches should be governed by the principles of: maintaining ecological balance in the regions where they will be implemented; ensuring that they will enhance, not encumber, local livelihoods; and, respect the planetary boundaries that govern all natural resources.

Priority questions for the study

- Which agro-residues contain usable fibres, obtainable through existing or promising processes?
- Where are these agro-residues available and accessible in large quantities?
- Where do they overlap spatially with existing or potential processing capacity?
- What are the cost, technical and logistical factors involved in converting agro-residues to usable feedstock?
- What are the socio-economic, environmental and sustainability considerations?

1

Background and Scope

1 Background and Scope

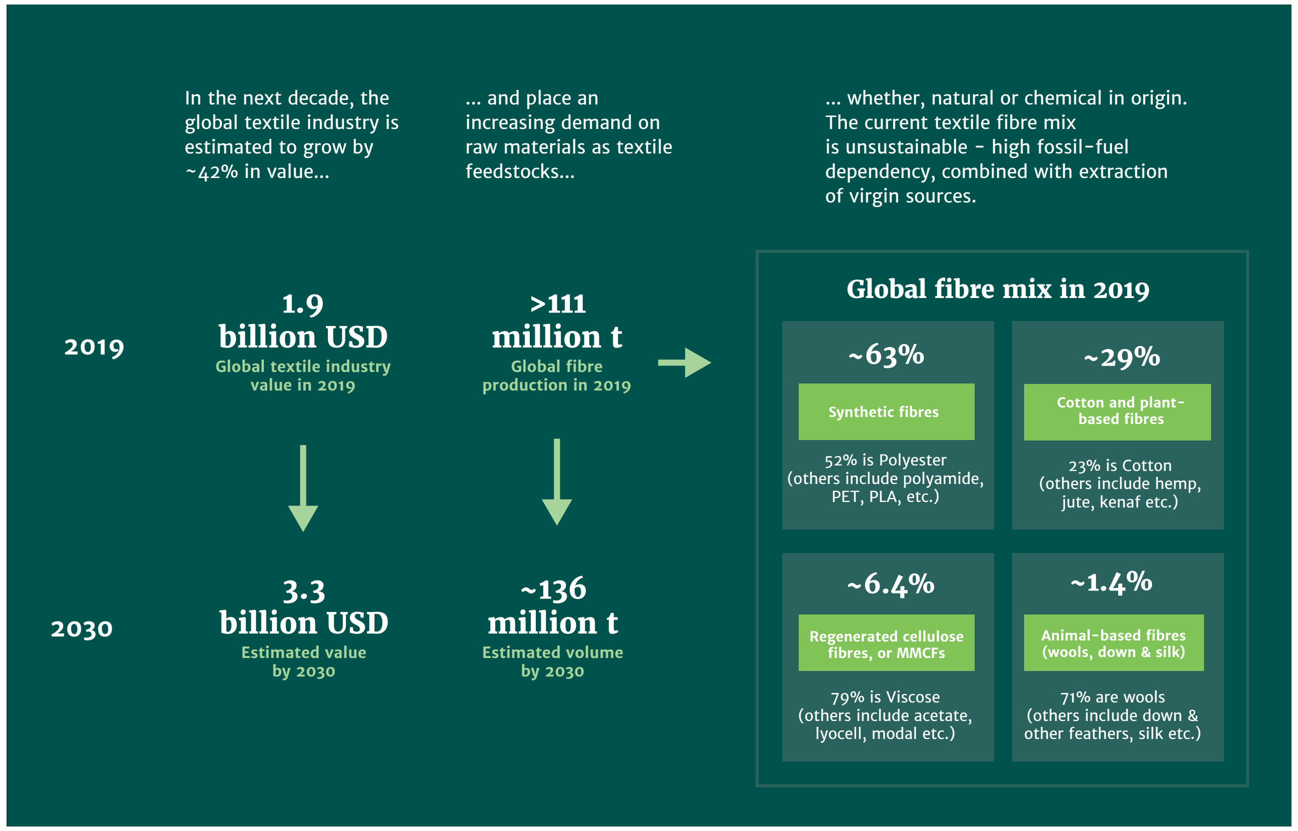
1.1 Context

Apparel production: A huge influence on environmental resource consumption

Clothes constitute a basic need, and the textile and clothing industry meets this need with a staggering volume and variety of products. In the last decade, this industry has grown by leaps and bounds, bolstered by megatrends like a growing global population, increasing income levels, "fast fashion", rapid urbanization and rapidly maturing markets in the Asia-Pacific. In 2019, the global textile industry was valued at $1.9 trillion and by 2030, it is estimated to touch $3.3 trillion (Pulse of the Fashion Industry 2019). Textile production places a large demand on resources like water, energy, chemicals, as well as sources of fibre feedstock both natural and synthetic. Globally, total fibre production has doubled in the last twenty years and in 2019, it crossed 111 million tonnes, the highest point to date. By 2030, this is expected to grow by nearly 35 million tonnes, as per pre-COVID estimates (Textile Exchange 2020). Of this, synthetic fibres such as polyester, polyamides and nylon form nearly two-thirds, with the remaining shared between natural and manmade cellulosic fibres (MMCFs).

An unsustainable fibre mix

The current fibre mix in the textile industry is not sustainable. Synthetics, despite their low prices, conducive properties and wide range of applications, are not viewed favourably due to their fossil fuel origins, heavy processing requirements and intensive chemical use. As the larger global sentiment shifts decisively towards conscious consumption and production, natural fibres such as cotton, linen, hemp, ramie and jute are seeing a resurgence among consumers. The latest figures estimate that the global cotton production is around 26 million tonnes, with over 80 countries involved in its cultivation (OECD/FAO 2020). However, only one-fourth of this volume is cultivated using sustainable, and environmentally and community conscious measures like Better Cotton Initiative (BCI), Fair Trade, Organic Cotton, International Sustainability and Carbon Certification (ISCC) and others (Textile Exchange 2020). Conventional cotton continues to have the largest share in total cotton production, with prevailing practices relying on high water demand, heavy chemical dependency, intensive land use and forced labour. (CottonUP; US Department of Labour 2020; WWF). With several low- to middle-income countries in Asia and Africa engaged in cotton cultivation and also having greater vulnerability to climate risks, its future as a textile feedstock relies on its ability to transition to sustainable production practices.



MMCFs, which are natural polymer structures developed from cellulose sources (mainly wood and bamboo) through a pulping and extrusion process, are viable alternatives to natural and synthetic fibres. Viscose, lyocell, modal and cupro provide significant functional advantages over natural fibres and have much lower processing requirements than synthetic fibres. Since the 1990s, MMCFs have more than doubled their market share in terms of output from three million tonnes (Fashion for Good 2020), and are projected to grow at a six percent CAGR in the next three years (Textile Exchange 2020). MMCFs produced using closed loop processes, such as EU's BAT and ZDHC's MMCF Guidelines, and sustainable forestry standards offer sustainable options. However, two major issues plague MMCFs: first, responsible sourcing, as they require large-scale forest fragmentation and deforestation, a third of which takes place in ancient and endangered forests; and second, proper management of hazardous chemicals used in processing through re-use and recycling (Canopy Hot Button Report 2020).

This largely linear production model places a huge burden on virgin resources, energy and the environment, thus prompting a shift to recycled alternatives, including used textiles. rPET, or recycled polyester, utilises existing pre- and post-consumer plastic waste[2], to produce fabrics and retains most of the qualities of virgin polyester. From 2009-2019, the market share of rPET in the apparel and garment industry has grown from 9% to 14%, propelled by the growing athleisure trend in garments, footwear, jackets and bags. Textile wastes, including post-industrial scraps, used garments, vehicle upholstery and household items, also find use as raw materials for textile production. Globally, the recycling of textiles is slow on the uptake, with only 12% of the material used for clothing and textiles undergoing downcycling or cascaded recycling[3], and less than 1% following closed loop recycling[4] (Ellen MacArthur Foundation 2017). Nike, H&M and Patagonia are some brands driving initiatives for the collection and recycling of used textiles.

The jury remains divided on "how much" better are these recycled alternatives. Although recycled materials are driven by the principles of circular economy[5], they do not provide a complete solution. A major sticking point surrounding recycled fibres is the discrepancy in calculating their overall environmental impact – current calculations methods do not account for their first life impacts; if these were to be included, then a different picture would emerge (Rengel 2017). Besides this, the recycling process has limited iterations. Each iteration in the mechanical recycling process causes the original fibre to lose critical properties like strength, durability and elasticity, necessitating reinforcement through intensive chemical processing and blending with virgin raw materials (Brancato 2008).

A search for better alternatives and new starting materials

These alternatives answer only a part of the most important question faced by the textile industry, and the world at large: how can the global textile industry lower its harmful impacts and become more sustainable? On its present growth trajectory, characterised by destructive megatrends like rising demand, mass production and limited re-use and recycling, by 2050 the textile industry will have: consumed 300 million tonnes of non-renewable

2 rPET can be made from both post-industrial and post-consumer wastes such as plastic bottles, ocean waste, pre-processing fabric scraps and discarded polyester clothing.

3 This refers to the recycling of clothing into lower value applications like insulation material, wiping cloths or mattress stuffing.

4 This refers to the recycling of clothing into the same or similar quality applications.

5 While enabling a circular economy, such alternative uses of recycled bottles may not address the primary issue, i.e., the unsustainable, mass production of these products, in the first place.

inputs[6]; taken up 26% of the carbon budget associated with the 2^{0}°C pathway; and added 22 million tonnes of synthetic microfibres to the world's oceans (Ellen MacArthur Foundation 2017). The profitability of the industry also faces dire prospects – by 2030, textile brands could face profit losses of up to 52 billion USD per year in the business-as-usual scenario (Pulse of the Fashion Industry 2017). These projections inject extraordinary urgency into a drive to alter this course and ramp up efforts to identify, support and scale alternative, low-impact and sustainable innovations through coordinated action.

Bio-based materials innovations: Unlocking the potential in South and Southeast Asia

Several distinct solutions have been outlined to achieve sustainability in textile production – among them, materials innovation stands out in terms of promise. The appeal for materials innovation lies in the fact that it looks closely at the root of the textile sustainability conundrum, and provides solutions from the bottom up. In a recent global survey, close to 67% respondents from the fashion industry indicated that using innovative and sustainable material mixes is an important focus area for their brand (The State of Fashion 2020). Global brands are exploring alternatives to the standard material mixes in textile production to include more sustainable substitutes that can still perform on function and aesthetics. Leading experts postulate that future research and development efforts in textiles will increasingly focus on material sciences in the search for new fibres and textiles that can be scaled. At present, innovations in developing novel biomass materials or unique combinations of existing materials in textiles take place at a smaller scale, often restricted to the laboratory and pilot stages. A few of these have reached commercial level, backed by global brands like BESTSELLER x Spinnova, Tommy Hilfiger x Frumat and Adidas x Bolt Threads.

A recent but surging trend within this space is the industry's spotlight on bio-based materials. In the last few years, rising industry-wide consciousness and acknowledgement of consumer perceptions and ethical/environmental concerns are driving textile innovators and brands to greater efforts to identify sustainable alternative materials, especially those with natural origins.

Box 1.1: Understanding "bio-based" materials

There is a growing buzz around "bio-" prefixed terminology, some of which includes bio-materials, bio-based, bio-design, bio-fabricated and bio-assembled. While there is a high chance of generalization, ambiguity and erroneous usage of these terms, each carries distinct meanings and implications, which are covered with refreshing clarity and depth in a recently published report (Biofabricate and Fashion For Good 2020).

For the purposes of this study, the authors define bio-based materials or products as those that are "wholly or partly derived from biomass, such as plants, trees or animals (the biomass can have undergone physical, chemical or biological treatment)", as outlined by the European Committee for Standardization European Committee ("Bio-based products").

Currently, several mainstream textile materials are bio-based including cotton, silk, wool, linen, leather and jute. While plant-based or cellulose fibres are generally preferable over those that are animal-based, the former still incur significant environmental costs in terms of water, energy and nutrients. An evolved understanding of product sustainability in textiles, encompassing the entire life cycle – from raw material extraction, to land use change, to manufacturing, and then to transportation, end-use and disposal (Amos 2019) – underscores the need for bio-based "alternatives." The industry needs more sustainable options that utilise existing and available plant-based biomass, require no additional resources from their journey as raw material to textile fibre, and have overall lower production impact vis-à-vis traditional production processes. Wood-based residues are a source of bio-based alternatives being used in textiles (Forest for Fashion 2017), but there are concerns around their sourcing, and ecological as well as carbon impacts constrain their solution potential.

Some textile innovators like AltMat, Orange Fibre, Green Whisper and Agraloop, in collaboration with Fashion For Good's Innovation Programme, are exploring bio-based alternatives through proprietary products, processes and technologies that have been successful in producing cellulose pulps or fibres from pineapple leaves, hemp, citrus fruit waste, banana stem and food-crop waste (flax and hemp), respectively. These pulps and fibres are then used in manufacturing textiles and garments. Each of these innovators, along with others in this space, relies on a specific bio-based feedstock and operates at small scale.

Another promising domain within bio-based textile alternatives that has yet to be thoroughly explored, is – agricultural residues and waste (see Box 1.2 for definition).

Agro-residue biomass is a by-product of agricultural activities and can be found in abundance across the world. Sustainable management of these residues is among the key challenges accompanying a growing agricultural sector. Particularly in Asia, which accounts for 63% of global agricultural value and has the largest share of cropland (~38%), abundant volumes of agricultural residues pose a formidable environmental threat. The inability of agrarian communities to re-use, dispose of and manage these large volumes of residues, leads them to opt for low-cost, low-effort options like mass burning to clear their fields for the next season. Domestic uses like fuel, fodder, animal bedding, mulching and composting, and even industrial uses, can only utilise a small part of these residues. Countries in South and Southeast Asia that depend heavily on agriculture, are particularly vulnerable to environmental damage and pollution resulting from large-scale residue burning.

In India, which is the second largest agro-based economy in the world and employs a year-long cultivation system (FAOSTAT 2020), 500 million tonnes of agricultural residues are generated annually. After their utilization as fuel, fodder and other domestic and industrial uses, a surplus of about 140 million tonnes of residues remains, of which about 92 million tonnes are burnt[7]. For most farmers, residue burning is a convenient route with negligible costs for preparing the field for the next sowing season, as opposed to hiring combines to remove residues. A study by the Indian Agricultural Research Institute estimated that residue burning releases 149.24 million tonnes of carbon dioxide, 9 million tonnes of carbon monoxide, 0.25 million tonnes of sulphur oxides, 1.28 million tonnes of particulate matter and 0.07 million tonnes of black carbon each year (Jitendra et al. 2017). This adversely affects air quality levels in the region, and especially for nearby towns and cities, endangering both the environment and society.

This problem is not limited to India. Due to high agricultural dependency in South and Southeast

Box 1.2: Defining agricultural residues and waste

Generally, agricultural wastes refer to waste materials derived from agricultural operations. The United Nations defines agricultural waste to include manures and other wastes from farms, poultry houses and slaughterhouses; harvest waste; fertilizer run-off; pesticides entering water, air and soil; and, salt and silt drain from fields (Nagendran 2011; UN 1997; OECD 2011).

In this study, agricultural waste and residues (or agro-residues) will primarily refer to harvest residues, also known as crop residues. Crop residues comprise both field residues and process residues. The first refers to the residues left in the agricultural field or orchard after the crop is harvested; some examples are stalks, stubble (stems), leaves and seed pods. The latter refers to the residues left after the crop is processed into a usable resource; common examples are sugarcane bagasse and molasses (Agamuthu 2009; Hoornweg and Tata 2012; Obi, Ugwuishiwu and Nwakaire 2019; UN 1997).

6 Non-renewable inputs comprise of oil for producing synthetic fibres, fertilisers to grow cotton, and chemicals for producing, dyeing and finishing fibres and textiles.

7 Estimates by Ministry of New and Renewable Energy, Government of India.

Asia, several countries including Indonesia, Myanmar, Vietnam and Bangladesh also opt for the slash and burn method of agriculture. The mass burning of agricultural residues and forests (specifically, oil palm plantations in Indonesia) caused the infamous Southeast Asian Haze in 2015. A study estimated that in the period from September to October 2015, the total carbon emissions from these fires was 0.23 million tonnes, of which 83% was carbon dioxide, 16% was carbon monoxide and 1% was methane (Huijnen et al. 2016). Once environmental aberrations, these events are becoming more commonplace and have long-lasting and negative ripple effects on the environment and quality of life.

Identifying, supporting and scaling up innovations that use agro-residues as a bio-based alternative feedstock for producing textile fibres, can provide a solution to most of these issues. Several studies have found these residues to be readily available lignocellulosic alternatives to mainstream plant fibres like cotton due to their similar structures, composition and properties. These properties can support the use of agro-residues in applications like textile, paper and packaging. Some of the major lignocellulosic crop residues are wheat straw, rice straw, barley straw, corn stover, sorghum stalks, coconut husks, sugarcane bagasse, pineapple leaves and banana leaves (Adhikari, Nam and Chakraborty, 2018; Panthapulakkal and Sain 2015).

With advances in textile material innovations, specifically those involving crop residues, there lies an unexplored pathway to developing mutually beneficial solutions to drive sustainability and reduce the impact of the textile industry as well as the agriculture sector. For South and Southeast Asian countries with growing market economies, rising spending levels and resource abundance, these material innovations can prove to be strong drivers for economic development and sustainable growth in the region. Grounded in conscious consumption and production, these innovations offer unique potential to advance systems-level thinking and dismantle a traditionally silo-based approach to achieving sustainability goals, generating co-benefits for a large number of stakeholders. Subsequent sections will expand on this opportunity and delve deeper into the technical and economic feasibility of textile innovations using agro-residues as fibre feedstock, with a specific focus on South and Southeast Asia.

1.2 Scope of the study

1.2.1 Overview

This report is the outcome of a detailed assessment of the geographic scope, technological and economic feasibility, and commercial viability of using agricultural waste and residues as alternative sources of raw materials to produce textile fibres. A key driver behind this assessment is to address the high synthetic material dependency of textiles and promote sustainability in textile production, by exploring alternative natural sources through mapping economical value chains, fostering innovative technologies and supporting industrial applications. The goal is to identify and enable practicable, innovative solutions that enhance resource efficiency and reduce the environmental burden of the textile industry.

The report focuses on identifying cellulose-based biomass sources for two types of textile fibres – agricultural fibres and manmade cellulose fibres (MMCFs). Other types of fibres, like animal-based fibres and synthetic fibres (made by polymerization of monomers to polymers like polyamide) are not part of the study scope. Biomass sources from agricultural waste streams and crop residues found in eight South and Southeast Asian countries – Bangladesh, Cambodia, India, Indonesia, Pakistan, Sri Lanka, Thailand and Vietnam – form the geographic scope.

The assessment involved rigorous scientific efforts, primary and secondary research and analysis, GIS mapping, ground validation exercises, stakeholder consultations, and overall viability assessment to ensure a high degree of practical value in the project's findings and recommendations.

1.2.2 Approach and Methodology

1.2.2.1 Technical viability assessment

The starting point for this report on technical viability was the publication "Textiles for Circular Fashion Part 1: Fibre Resources and Recycling Options" (Harmsen & Bos 2020). This was supplemented with desktop review and secondary literature study. A basic classification of textile fibres is made on the basis of biomass into agricultural fibres, MMCFs and bio-based synthetic fibres. Along with this, an overview of current state-of-the-art processing routes for fibre production are described. Finally, the current landscape of various innovators in the fibre processing and textile manufacturing field is developed using inputs from the stakeholder consultations (see Section 1.2.2.4).

1.2.2.2 Statistical and Spatial analysis of residues

A detailed statistical analysis of existing databases on agricultural production and land was carried out to identify suitable crop residues from the study regions, and was then spatially analysed to identify the best hub locations. Existing secondary databases like FAOSTAT 2018 were statistically analysed, and gaps were supplemented by primary methods like stakeholder consultations. A five-step methodology was developed to carry out the statistical assessment.

Selection of suitable agricultural residues from the eight countries

As a first step, it was critical to outline and define the two major types of residues, primary and secondary (see Box 1.3).

A systematic quantitative assessment of the most recent data (from FAOSTAT 2018) on total agricultural production volumes (in tonnes, t) and cultivation areas (in hectares, ha.) was carried out to understand the major crops in each of the eight countries.

Box 1.3: Defining primary and secondary agricultural residues

Agricultural residues (also called crop residues or agro-residues) in this study are distinguished into two categories: primary and secondary. Primary agricultural residues are found at the source where they are produced, like agricultural fields, plantations or orchards. These residues consist of the biomass that remains after the main product of the crop (for e.g., fruit, grains) is harvested. Some examples are straw, stalks, stubble (stems), leaves, prunings and seed pods.

Secondary agricultural residues refer to the residual biomass that remains after the crop is processed into a commodity at the processing mill. Common examples of these are sugarcane bagasse and molasses that are co-products of the sugar extraction process and are found in sugar mills. Similarly, when rice is processed it is de-husked, which results in secondary residues in the form of husk. After the rice is polished to produce white rice (final product), the resulting secondary residue is bran.

Box 1.4: Assessment of the technical potential of the residual agricultural biomass

Technical potential represents the absolute maximum amount of residual biomass that is potentially available in the field (in case of primary residue) or at the processing mill (in case of secondary residue), by assuming the absolute minimum of technical constraints and the absolute minimum constraints from competing uses and sustainability constraints. It is calculated using the following formula:

Residue yield [t/dry matter] = **crop area** [ha] * **yield** [ton/ha] * **RPR** [-] * **DM_content** [-]
Here,

- Crop area is derived from FAOSTAT 2018 figures for each country.
- Yield level of the main product (like grains for cereals, sugarcane stems etc.) is derived from FAOSTAT 2018 figures for each country.
- RPR levels are derived from different sources (see Annexure 1 for details on the values used per crop).
- DM content stands for dry matter content in the crop (see Annexure 1 for levels used per residue).

Residue-to-product ratio (RPR) refers to the ratio between main crop product (e.g., grains, sugarcane stalk) and the amount of residue (e.g., the straw or trash) in kg dry matter (dm) per tonne. The RPR ratios used in this study are based on former studies done by WUR in different countries in the world. The RPR ratio therefore refers to an average and does not take into account specific crop varieties or local production factors. This technical residue potential is applied to make a first selection of crop residues with large technical abundance in the eight focus countries of this study.

From this, a longlist of top crops was developed by selecting the most important crops in terms of production volume and area under cultivation. The authors ensured that the top crops of all eight countries were captured. For the top 30 crops on this list, the primary and secondary residues were identified and their technical potential was assessed (see Box 1.4). These were also further characterised in terms of cellulose and fibre content.

The longlist of residues was further narrowed down to a shortlist by using certain pre-determined criteria for biomass following the two main processing routes: cellulose based and fibre extraction. The criteria for each route are:

For cellulose pulp

- At least 30% cellulose content
- Availability of at least one million tonne/year/country
- Reasonable expectation of a large unused residue potential

For fibre extraction

- Degree of polymerization, or DP, should be over 2500
- Should belong to a fibre plant family
- Should be identified in literature as suitable for fibre extraction

For cellulose pulps, the last criteria on large unused potential implies that the residual biomass is likely to have limited competing uses, and/or its conversion into textiles would be an acceptable alternative sustainable use option. A large unused potential is particularly evident when the selected crop residues are being burnt on the field.

For fibre extraction, the minimum availability of residues was set much lower, because the sizes of fibre extraction plants can be much smaller than for cellulose dissolving factories (see Box 1.5 for examples of larger existing factories)

In this study, hub identification was done by defining different mill sizes for cellulose dissolving plants on the basis of their production capacities. Building on the findings presented in Box 1.5, the following mill sizes were defined – for fibre extraction, a standard mill size of 100-1000 tonnes of fibre per year; and for the cellulose dissolving plants, three sizes were outlined:

I. Small-scale mill, which produces 75 kilotons of cellulose per year.
II. Medium-scale, or intermediate mill, which produces 150 kilotons of cellulose per year.
III. Large-scale mill, which produces 500 kilotons of cellulose per year.

To bring into perspective the biomass demand for the different mill sizes: assuming that at least 30% of the cellulose can be extracted from residual biomass sources, the large size mill will require at least 1,600 kiloton dm biomass each year. Large size mills with this demand quantum are expected to strongly impact the local market for residues. Additionally, such biomass requirements cannot be fulfilled by sourcing only one type of agricultural residue. Keeping this in mind, the delivery chains designed in this study also review the option of combining different types of agro-residues that can be sourced to a cellulose dissolving plant. Pre-treatment plants at intermediate stages are also set up to densify, dry and store the biomass before it is further transported to the cellulose dissolving mills (see Section 4.1).

Spatial analysis to identify hub locations

The final selection of residues, as discussed in the previous section, was the starting point for the spatial identification of hub locations. Based on the three sizes of cellulose dissolving plants (small, medium and large), a minimum demand for biomass was specified for each type of residual biomass on

Box 1.5: Examples of existing cellulose dissolving pulp factories and production capacity

While around 7% of the world's virgin cellulose pulp comes from non-wood vegetal sources (van Dam et al. 2018), the use of primary residual biomass from crops is still very limited. Most of the current vegetal sources come from harvested crops that are deliberately grown as feedstock, such as bamboo or eucalyptus. Mills that extract cellulose from wood or other renewable sources are generally range in size from 75-850 kilotons of cellulose production per year (see table below). These are mostly based on woody biomass sources (rich in cellulose, easy to transport) and are mostly aimed at producing cellulose pulp for the paper and viscose industry.

Table 1.1: *Examples of existing cellulose dissolving pulp factories and production capacity*

Location	Biomass source	Production capacity of cellulose pulp [Kton cellulose/year]
Portugal	Eucalyptus wood	115
Laos	Local Wood	250
Finland	Wood	430
South Africa	Wood	850

The largest factory is the SAICCOR mill in South Africa, using a sulphite process. The most recent expansion of this mill makes it possible to produce 800 kilotons of dissolved cellulose pulp per year. The feedstock used in this mill is eucalyptus wood grown at relative near proximity in Durban, the location of the SAICCOR mill. SAICCOR is only suitable for woody feedstock, and it is not realistic to assume a similar mill size for sourcing agricultural residues.

the basis of its cellulose content. For fibre extraction, the minimal demand for biomass in a hub location was assumed to be between 100-1000 tonnes of fibres per year; a real minimum demand was not set. Ideally, locations selected for sourcing yearly biomass quantities were mapped withing a radius of 100 kms. Therefore, the biomass density and total amount per region, in combination with the minimum capacity of the extraction mill, were critical in determining the best hub locations.

Using a geographic information system (GIS) analysis, the most promising hub locations were selected for the proposed biomass delivery chains for the eight focus countries. The spatial analysis involved mapping agricultural residues –primary residues, which rely on the RPR of the main crop yield, were distributed using the spatial crop production data from MAPSPAM; for secondary residues, like sugarcane bagasse and empty fruit bunch (EFBs) of palm oil, the locations of the sugar mills and palm oil plants were included respectively, and residue availability spatially linked. The combined information from these inputs was used to identify the most promising hub locations. The final locations were typically those having the largest and most concentrated availability of the shortlisted residual biomass in the focal countries.

A detailed discussion on the use of MAPSPAM and the techniques adopted for developing spatial maps is given in Annexure 4.

1.2.2.3 Cost assessment for at-gate delivery of biomass for cellulose and fibre extraction

Based on the initial review of the suitability of agro-residues for cellulose and/or fibre extraction, and the size of the technical potential available in every hub location selected, a few general delivery chain designs were developed for the sourcing of residues. These chain designs formed the basis for carrying out the cost calculations for delivering the residual biomass from the field (primary residues) or the mills (secondary residues), to the gate of the cellulose dissolving or fibre extraction plant in the hub.

The major factors considered for cost assessment include the following:

I. Purchase cost of the biomass
II. Compensation cost for the loss of nutrients lost from the field due to residue removal
III. Up and off-loading cost when the biomass is transported
IV. Densification cost in case of intermediate conversion to pellets before long distance transport
V. Storage cost in case biomass is not available year-round because of seasonality, despite the need to keep the cellulose dissolving mill operational year-round
VII. Transportation cost, which can be local, short and long distance.

It was assumed that currently unused residues are available for sourcing. Part of the residues are left on the land as fertiliser and part of the residues is burned to obtain heat and power for the processing of the main product from the biomass. In practice, other biomass that is less suited for the production of cellulose can be used for these purposes. This allows significantly larger availability of biomass residues. It is also possible to use by-products resulting from the cellulose and fibre extraction process as fertilisers and/or energy sources.

In the chain cost assessment, the return transportation cost was also included when the remnants of the biomass after extraction of fibres were suitable to be brought back to the fields as fertilizers. If this is not possible, an additional cost was allocated for fertiliser to compensate the farmer for the nutrients removed in the residue (see Section 4.2 and Annexure 5 for details).

1.2.2.4 Stakeholder mapping and consultations

The findings for the above components are based on the review of existing secondary databases and provide a strong, data-driven foundation for developing alternative sourcing models. It was critical to contextualize their applicability enhance through validation against on-ground realities. As agro-residue value chains rely on high interdependencies between the agriculture sector and textile industry, particularly in agrarian communities and related social entrepreneurship initiatives driving rural livelihoods, stakeholders' insights and perspectives are indispensable. These were captured through stakeholder consultations.

Stakeholder mapping and analysis

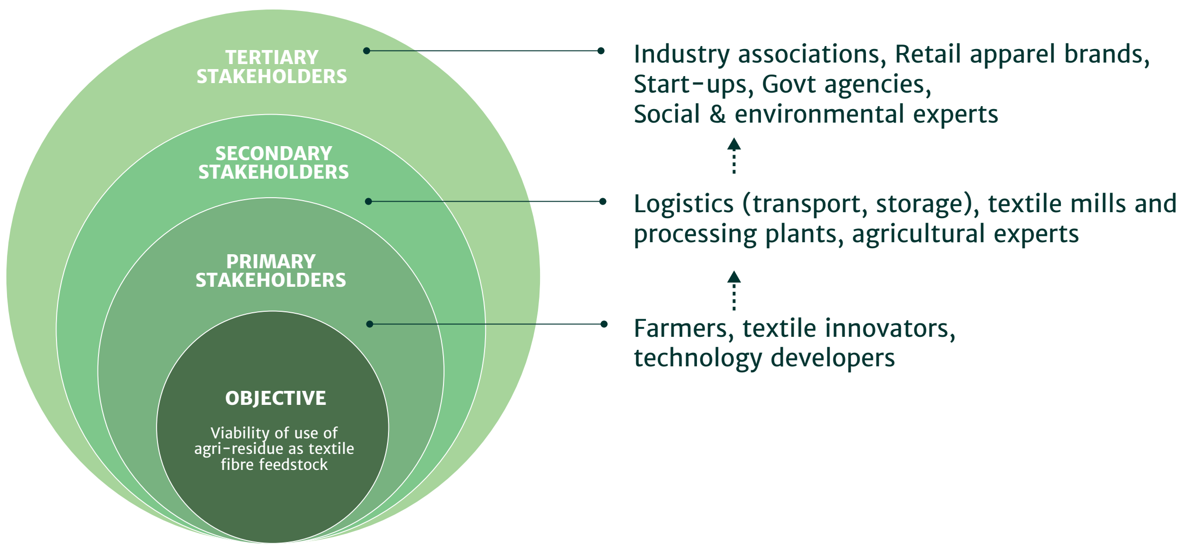
An extensive mapping exercise was carried out to identify a heterogeneous mix of stakeholders, representing diverse needs, influences and interests associated with the residue-based value chains. Preliminary examination of relevant literature was used to identify 11 major stakeholder groups and their geographic scope (see Figure 1.2). These stakeholders include both those who affect, and are affected by, a decision or action, whether potentially or currently.

An evaluation of the unique "stake" of these stakeholders, which is a combination of interests and influences, was carried out (see Annexure 6). These stakeholders were classified into three levels – primary, secondary and tertiary – depending on their ability to influence and operationalize alternate value chains based on agro-residues (see Figure 1.3). These stakes were further analysed to develop an interest-influence matrix to ascertain the level of importance of each stakeholder (see Annexure 6). This provided an understanding of the socio-economic dynamics for managing resources, and highlight the stakeholders with a comparatively dominant position in the ecosystem

Figure 1.2: *Identified stakeholders and their geographic scope*

Local / Regional	Pan-regional / Global
Farmers/Farmer cooperatives	Textile processors and manufacturers
Logistics network, including transport, storage etc.	Technology developers
Industry associations	Social and environmental experts
Apparel brands	Start-up organizations
Agricultural experts	Textile innovators and design experts
Government and its agencies	

Figure 1.3: *Classification of identified stakeholders across three levels*



of residue-based textile value chains. Additionally, this helped identify non-central groups, and in developing strategies on how best to ensure their representation (Reed et al. 2009).

Stakeholder consultations
Following the mapping and analysis, a comprehensive consultation plan was developed to gather the insights, perspectives, interests and experiences of the diverse stakeholder groups on the different factors related to the alternate value chains. Consultations were facilitated by questionnaires, developed to gather contextual and sectoral information on various aspects such as agricultural practices and systems; specialization in innovation and technology; textile fibre production; commercialization and market prospects; socio-economic implications; and the impact of climate change (see Annexure 7 for the question sets).

These consultations were conducted virtually via video-conferencing or through telephone calls due to COVID-19 mobility restrictions and other resource constraints. On occasion, these conversations were captured through recordings and interview notes. The stakeholder consultations were also helpful in filling in information and data gaps in the existing secondary literature like competing uses of residues, labour costs, fuel costs, local agricultural practices, fertilizer prices and local infrastructure for logistics.

1.2.2.5 Pre-feasibility and Landscape Assessment
Information on dominant trends, sectoral perspectives and contextual influences gathered through the stakeholder consultations was used to conduct a current landscape assessment for implementing agro-residue-based value chains for textile fibres. A pre-feasibility assessment was carried out to capture various factors affecting the alternative value chains that can act as barriers and opportunities (both potential and existing). These were categorised into five main pillars – agriculture; technology, design and innovation; processing and manufacturing; commercialization and scaling-up; and, socio-economic and sustainability perspectives (see Section 4.3). While some of these insights were more local and context-specific in nature (for e.g., agricultural practices, local infrastructural arrangement, existing market relations, pricing considerations and stakeholder networks), others were pan-regional (for e.g., advancements in innovations, fibre development techniques and industry outlook). For some factors, their potential effect on the proposed alternative biomass value chains will vary with time and regional developments.

1.2.2.6 Assessing the impact of climate change and environmental externalities
Climate change poses one of the biggest uncertainties globally. The resulting effects are crucial determinants in assessing possible threats and identifying vulnerabilities for the alternate value chains for textile fibres. Changes in climate variables like minimum and maximum temperatures, annual precipitation, amount of rainfall received per day as well as the moisture stress index, were analysed using predictions from an Ensemble Climate Model for RCP 4.5 scenario, for a medium-term scenario of 2040-59, as compared to baseline levels[9]. Besides this, the effects of climatic and environmental externalities on the selected crops across the focal countries – including the effect of disaster and diseases, the consequences of different cultivation practices (like monoculture), crop and residue burning and pesticide use that affect crops and by consequence, the agro-residues – were analysed. A comprehensive table providing insights on the impacts of climate change on shortlisted crops and their farming in the eight countries, the associated challenges, as well as emerging trends in promising in-country practices to build resilience against climate impacts, can be found in Annexure 8.

These analyses provide a macro-level picture of ways in which climate change, environmental conditions, and changing practices can affect the proposed biomass chains. An in-depth environmental impact analysis of these value chains will require a detailed life cycle assessment. This is not possible presently due to inadequate information on the impact of different processing stages, as well as the overall impact on the environment. Such assessments will become feasible when this sub-industry matures, and products made with these biomass residues near the end of their life cycles.

9 All Climate Projections arrived using Climate Change Knowledge Portal of World Bank Group. https://climateknowledgeportal.worldbank.org/

2

Understanding Fibres, Processing and Innovations

2 Understanding Fibres, Processing and Innovations

2.1 Fibre classification

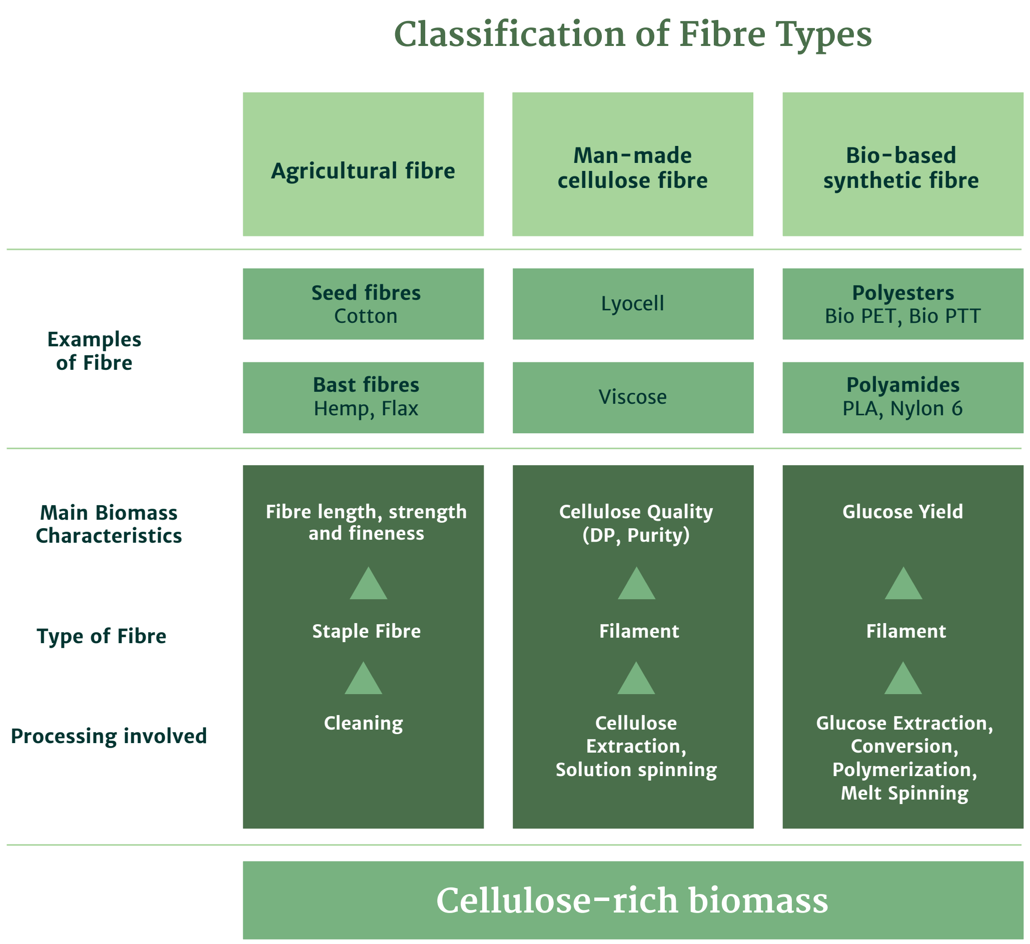
A transition from fossil fuels and virgin natural sources to alternative bio-based feedstock for textile fibre production, like agro-residues, requires a closer look at the different fibre types with bio-origins. Within the class of bio-based fibres, three major categories can be defined based on composition (cellulose and/or starch): agricultural fibres, manmade cellulose fibres (MMCFs) and bio-based synthetic fibres. Each of these fibre types requires complex processing for conversion into textile fibres. Figure 2.1 illustrates the major differences in these fibres.

Agricultural fibres

These have the highest potential for maintaining the natural fibre structure. Only specific plants are capable of producing agricultural fibres suitable for textiles. Agricultural fibres are obtained from various parts of the plants, i.e., seed, bast, leaf or fruit. Some examples include:

- Seed: Cotton, kapok
- Bast (stem): Banana, flax, hemp, jute, ramie, kenaf, hop, nettle
- Leaf: Abaca, banana, sisal, raffia, pineapple
- Fruit: Coir (from coconuts)

Figure 2.1: *Three main fibre categories and their production routes from biomass*



Not all agricultural fibres are suitable for textile applications. Fibres with high cellulose content and low or negligible lignin content are preferred, as lignin is known to provide structural strength to the plant and is less suited to apparel.

Agricultural fibres that are most ideal for textile applications are soft, long with a fine fibre structure, and high cellulose. Soft bast fibres like flax, which is used to make linen, have a wide range of applications in apparel. They have high cellulose and low lignin content, which is in sharp contrast to hard leaf fibres like abaca, banana and sisal, that contain both lignin and cellulose. Out of the different natural sources, seed fibres like cotton and possibly kapok are the most suitable for producing textile fibres.

MMCFs

MMCFs, or manmade cellulose fibres, are made from cellulose pulps extracted from biomass and then re-formed into new cellulose fibres (filaments). In theory, MMCFs can be made from all types of biomass containing cellulose; primarily wood, followed by cotton linter and bamboo, are common feedstocks for MMCFs, with microbial cellulose grown on food waste, recovered cotton and algae are emerging feedstocks.

Depending on the initial cellulose content in the biomass, major or minor processing is required to obtain MMCF that can be used for textile fibres. The main parameters for selection of biomass to produce MMCFs include composition (very high cellulose, no lignin) and length of the cellulose polymer (intrinsic viscosity and degree of polymerisation). Other parameters like the amount of ash or silica content are also important, as beyond a certain level these can affect the dissolution of cellulose.

Bio-based synthetic fibres

These fibres are made by the polymerization of monomers to form polymers. Synthetic fibres are originally made from fossil fuels, and examples include polyester (PET) and the polyamide nylon. Due to their non-renewable origins, the major challenge for synthetic fibres is to transition to viable renewable sources. The key to addressing this is glucose, which is the feedstock for making synthetic fibres which are then converted into a filament. Previous studies have shown that it is technically possible to produce all major monomers from biomass (Harmen et al. 2013). Monomers with acid- and alcohol functionalities, such as lactic acid and succinic acid, can be produced well from biomass like sugars (i.e., glucose), since the oxygen atoms needed for these building blocks are already present in the biomass. These findings pave the way for producing synthetic fibres from bio-based renewable sources, since the production route for bio-based polymers usually starts with a glucose molecule. The glucose molecule is converted by chemical means or fermentation to the target molecule. Accordingly, no specific type of biomass is required to produce synthetic bio-based fibres; the only requirement is that the selected biomass should contain glucose in the form of sucrose, starch or cellulose.

Box 2.1: Grasses, new fibre sources for textiles

Growing interest in alternative resources for textile fibres has focused attention on lignocellulosic agricultural by-products. These residues can be potential sources of glucose, cellulose (to produce cellulose pulp), or even vegetable fibres. Typically, grasses have hollow lignocellulosic stems with dense nodes.

By-products (residues) such as husk, bagasse and straw from crop plants like wheat, maize, rice, sugarcane, sorghum and barley are some commonly available sources of grasses. Besides these, plants like bamboo and miscanthus are partial sources of grass-based biomass. All these share some common features in lignocellulosic composition that includes 35-40% cellulose, 20-25% hemicellulose and 15-20% lignin.

Bamboo is widely used for production of cellulose pulps that are used to produce textile fibres (for e.g., viscose). About 7% of the world's virgin cellulose pulp is made from non-wood sources like straw, bamboo and bagasse (van Dem 2018).

2.2 Processing approaches

Textile fibres from cellulosic sources can be produced using a number of processing techniques, depending on the properties and characteristics of the fibre source. For agricultural fibre sources, the processing techniques focus on maintaining the natural fibre's cellulosic structure, either as single filaments or fibre bundles. For others like MMCFs and bio-based synthetic fibres, the processing focuses on extraction of cellulose and glucose, respectively, from the fibre source, then following a series of steps of produce the filaments that are processed into different fabrics. A brief description of the key processing techniques for different fibre types is given below.

Agricultural fibres

The key major steps for processing agricultural fibres include the following:

- Desiccation
- Harvesting
- Retting
- Decortication
- De-gumming / Cottonisation
- Refining

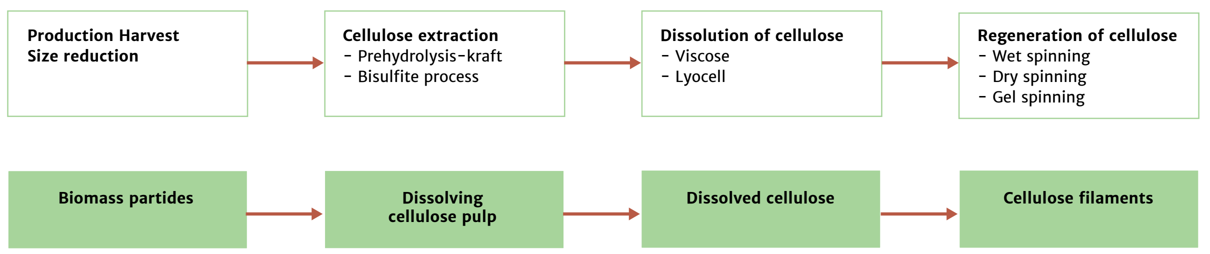
Specifically, depending on the part from which the fibre is sourced – seed, bast or leaf – different methods for harvesting and processing are used. Fibres found in bast (stem/stalk) and leaves are typically longer than those found in seeds, requiring different treatments for fibre extraction (see Table 2.1). The different types of fibres are:

- Seed fibres, like cotton fibres, are harvested and mechanically purified by a process called ginning, in which other plant material is removed from the cotton fibres.
- Bast fibres are separated from the stem by a process called retting. Retting is a chemical or biological treatment that removes soft tissue from the stem, resulting in fibrous material and a woody core as a residue stream.

Table 2.1 *Processing of different agricultural fibres*

	Seed	Bast	Leaf
Structure	Single fibre	Fibre bundle	Fibre bundle
Ultimate fibre length	Few centimetres	Metres	Metres
Processing	Ginning	Retting	Decortication

Figure 2.2: *Production route of manmade cellulose fibres from biomass*



- Leaf fibres like sisal are harvested mainly through decortication, a mechanical process where the non-fibrous tissues are removed by hand or machine. Other chemical processes are also applied to harvest leaf fibres.

MMCFs

MMCFs are produced by extracting cellulose from biomass sources, and subjecting it to a sequence of processing steps to produce a filament. The level of initial cellulose content in the biomass source determines the degree of processing required. The three main steps involved in processing MMCFs include cellulose extraction, cellulose dissolution and cellulose regeneration. The latter two are often combined and carried out in the same pulp mill. Figure 2.2 provides an overview of the production route from biomass to MMCF.

Cellulose extraction: Cellulose is strongly embedded in the lignocellulosic matrix in plants, which also includes hemicellulose and lignin. Cellulose polymer can be used only after its extraction from this matrix through a pulping process, which is designed to remove most of the lignin, hemicellulose and other extractable materials, while avoiding the degradation of the cellulose polymer. The conditions for the pulping process are adapted to the biomass type (such as hard wood, soft wood etc.).

Some conventional pulping processes are shown in Figure 2.3. These processes are based on sulphur content pulping, followed by chlorine-based bleaching chemicals in most cases. Dissolving pulps (highly pure cellulose fractions of >90% cellulose) are generally produced by acid sulphite or pre-hydrolysis kraft pulping process.

Dissolution and regeneration of cellulose: To obtain cellulose in liquid form, it needs to be dissolved or chemically modified, as unlike many petroleum-based polymers it does not melt upon heating (Olsson and Westman 2013). Different chemical solvents and reagents are used to dissolve and regenerate cellulose to produce cellulose filaments. Viscose and lyocell, some of the most widely used MMCFs in textiles, are produced through a number of steps that involve different chemicals. The viscose process is long and involves heavy use of toxic chemicals like carbon disulphide that have harmful effects on the environment.

Figure 2.3: *Production of cellulose extraction to produce a dissolving pulp from wood (Mather and Wardman 2015)*

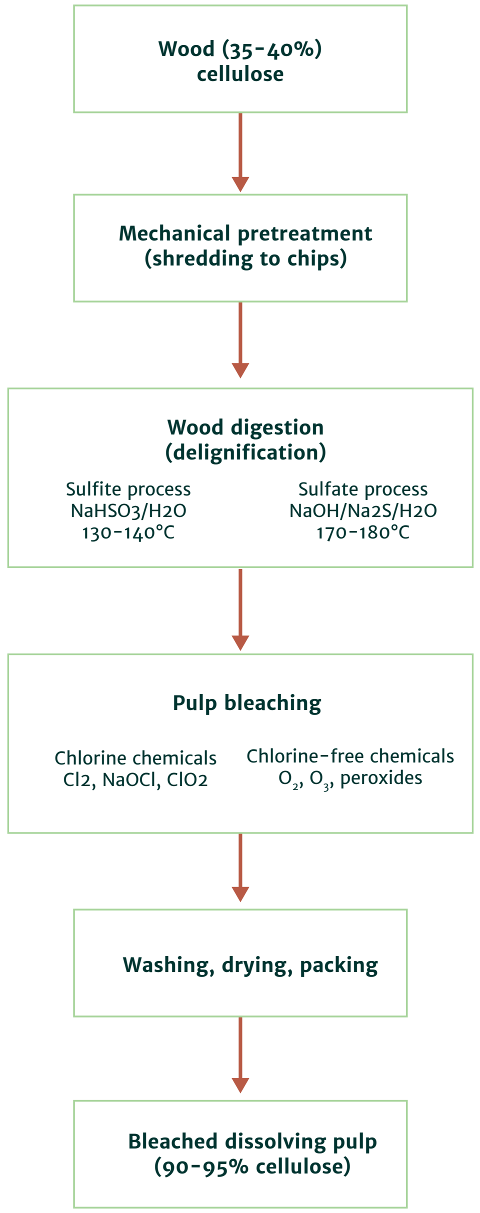


Figure 2.4 *Key stages in the manufacture of viscose and lyocell fibres (The Chemistry of Textile Fibres, R. Mather, 2nd edition)*

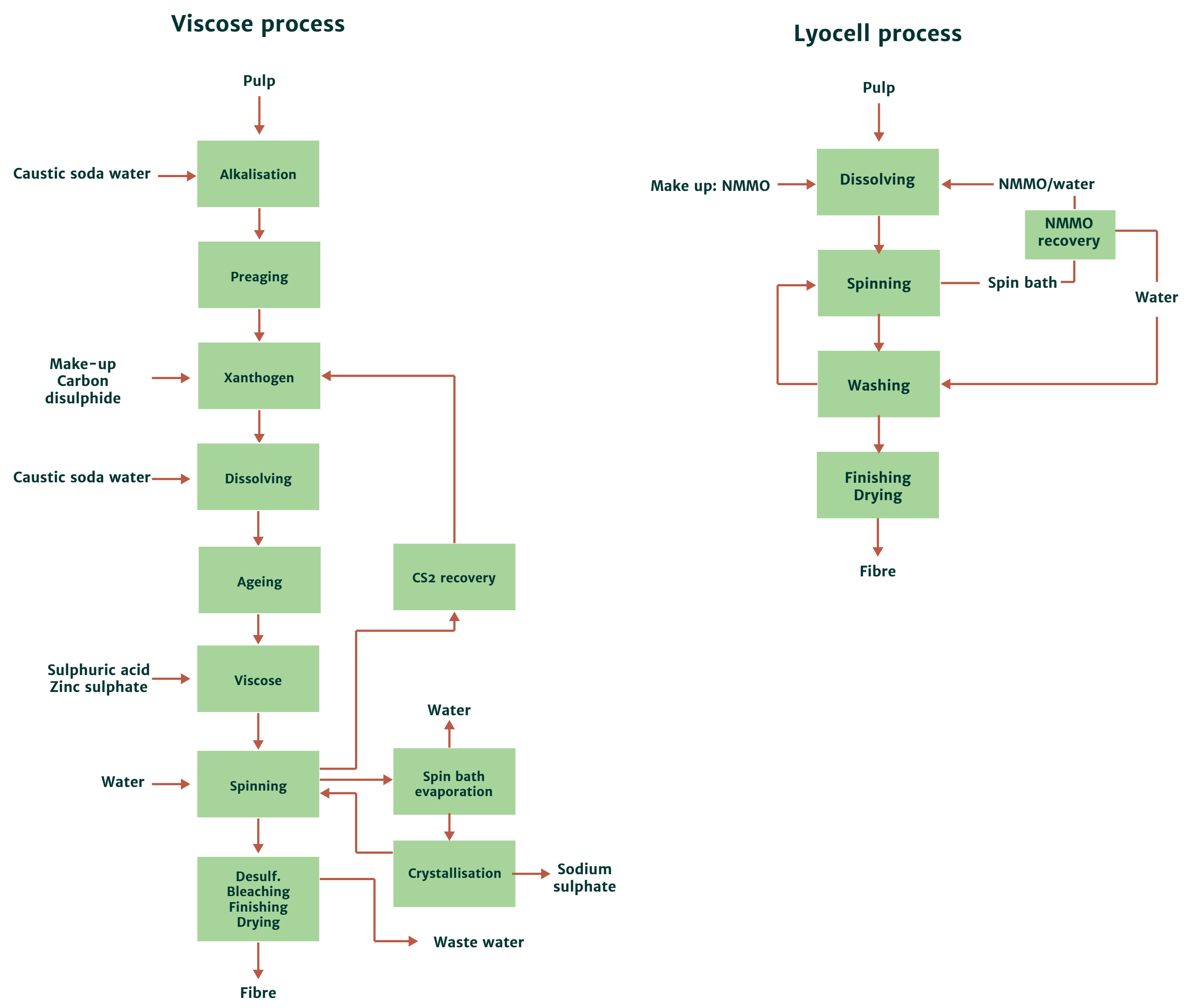
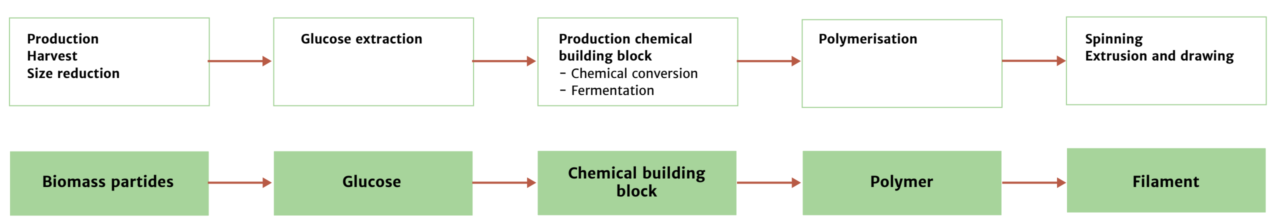


Figure 2.5: *Production route of biomass to bio-based synthetic fibres*



Efforts devoted to finding better alternatives led to the development of the lyocell process, which is more environmentally friendly. Further efforts are underway to finding alternative solvents for cellulose, and low-impact processes for MMCFs.

Bio-based synthetic fibres

Synthetic fibres, traditionally made from polymerizations of fossil fuel-based monomers, can also be made from renewable bio-based sources. For this, glucose, found in several biomass sources, forms the critical feedstock and is converted into a filament. The key steps included in this processing are: first, glucose extraction from the biomass; second, production of a chemical building block (monomer); third, polymerization to a polymer; and fourth, spinning to form a filament that can be spun or woven to a textile. Figure 2.5 provides an overview of this process (the pink blocks represent commodities that can be produced at different factories).

Processing innovations for agro-residues as feedstocks

With advancements in textile manufacturing, these processing methods have undergone numerous iterations to improve efficiency, reduce costs and lower environmental impact. In the case of agro-residues as fibre feedstock, these methods can be used in different combinations and modified to suit the type and composition of a given agro-residue to produce cellulosic textile fibres. After extraction of fibres/cellulose from these residues, additional processing is required to enhance their functionality and increase textile applications. Apparel production in particular requires high-quality fibres that are soft, durable and can be easily dyed, among other desirable properties. Blending with conventional fibres like cotton is a highly preferred route for most textile innovators to enhance the functional aspects of fibres from agro-residues. Most textile manufacturers opt for chemical-based processing methods due to their efficiency, higher yield and potential for permutations that can yield higher quality cellulose with wider applications. While doing so, it is important to be wary of the potential consequences arising from these processes, particularly as environmental and social costs.

Low-impact processing methods to produce agro-residue based textile fibres are also being explored. Several such innovations are supported by Fashion For Good's Innovation Platform, that works extensively with textile innovators and businesses that have sustainable sourcing and fibre processing methods, to accelerate and scale their models. The next section looks at the current innovator's landscape in textiles more closely.

2.3 Innovator's landscape

The last decade has seen a flurry of innovators demonstrating great promise with successes in fine tuning residue processing technologies. Collaborations between fashion designers, brands, industries and experts have enabled these innovators to test different residue types either as standalones, or via a combination of blending approaches. The following matrix (Table 2.2) maps out the current landscape of innovators, technologies and residue types. This list covers only a part of the diverse and vast landscape of innovators working with novel biomass sources, such as agro-residues, for textile fibre and apparel production, some of which are happening in real time with limited outflow of information.

The move towards sustainable fashion, being led by prominent artists, fashion designers, and apparel professionals, is creating a positive feedback loop for companies and consumers to create and meet demand. Several prominent global fashion brands are joining hands with innovators to bring products from alternative materials to mainstream consumers. Waste and residues from sources like apples, pineapples, citrus fruits, cactus, mushrooms, algae are steadily entering the apparel and textile market through products like bags, shoes, clothes and leather goods.

South Asian countries too are joining this vanguard. Start-ups in this region are producing fibre and leather from alternative bio-based materials at a small scale, in collaboration with local artisans and weavers. Some have found success in using a diverse mix of residues from banana, pineapple, sugarcane, eucalyptus, corn, lotus stems, and other crops as the raw material base for textile products.

The innovators' landscape is in a state of flux, evolving and experimenting at incredible speed – with a con-

Table 2.2 *Innovator's landscape*

Conventional	Agro – Residues (Field)	Agro-residues (Process)	Recycled Streams
Flax, Hemp: 9Fiber Agraloop StexFibre Bast Fiber Technology Boheco Bastcore The Hurd Co. Gencrest AltMat Bear Fiber The Hampley Backpack **Jute:** FarFarm Ecoloom Castanhal **Nettle:** Himalayan Wild Fibres	**Nettle:** Gesine Jost **Kapok:** Flocus Kapok Knot **Fruits:** Agraloop (banana) Pinatex by Ananas Anam (pineapple) **Date palm:** Palmfil	**Bagasse:** Louisiana State University **Floral stems:** Raydan Phool Samatoa (lotus) DUPONT™ SORONA **Potato:** Chips Board (Parblex) **Dairy:** QMilch DueDiLatte **Fruits:** Green Whisper (banana) AltMat (banana) Melior Handbags (pineapple) Orange Fiber (citrus fruits) Fru-Mat (apple) Von D Shoes (apple) Samara Bags (apple) Beyond Leather (apple) **Mushroom:** Bolt Threads (Mylo) MycoTex Ecovative **Algae:** Algi-Knit ECOPEL Busatti (Mario the Blanket) **Wood:** Spinnova Tree to Textile Circular Systems Fiber-X	**Wine / Beer residues:** Vegea (grape-marc) Nanollose **Textile waste:** Ioncell Infinited fiber Evrnu Refibra RENEWCELL Circ Re;code Suave Birla Cellulose **Floral stems:** Pond Textile **Coconut:** Nanollose (bacterial cellulose) **Mushroom:** Amadou Leather **Algae:** Algalife Algi-knit **Wood:** Birla Cellulose

* The above list is illustrative and does not comprehensively cover all innovations, some of which are emerging or evolving in parallel with this report

certed effort across academia, designers, manufacturers and brands. Factories across textile hubs in Tirupur, India and Dhaka, Bangladesh have quietly been stepping up manufacturing capacities for integrating the use of bio-based materials. However, in spite of the early promises and successful pilots for vegetable and plant-based approaches, the arena for use of residues across rice, wheat, maize, sorghum, bagasse, oil palm and other sources is still wide open and remains relatively unexplored.

3

Availability of Crop Residue in Regions

3 Availability of Crop Residue in Regions

3.1 Longlisting of crops and residues in the eight countries

The eight focal countries for this assessment from South and Southeast Asia—Bangladesh, Cambodia, India, Indonesia, Pakistan, Sri Lanka, Thailand and Vietnam—are known for their abundant agricultural activities with a wide variety of crops under cultivation. This provides a large range of potential cellulose-based feedstocks that can be used to produce textile fibres.

From the eight countries, a long list of desirable crops was developed for screening their suitability to produce cellulose pulps, or to extract fibres, on the basis of two parameters – first, the total area under cultivation in hectares (see Table A1.1 in Annexure 1), and second, the total annual production volume in metric tonnes (see Table A1.2 in Annexure 1). The latter was determined to be a better estimate of the indicative amount of residual biomass that can be available on the ground. To maintain uniformity in crop selection across regions, it was ensured that the longlist included the top 20 crops from each country. Then a ranking was carried out for these crops for the eight countries (see Table A1.3 in Annexure 1).

Some key trends were observed after the analysis:

- **Rice is the most abundant crop across the eight countries,** with 30% of the total cultivation area (~97,216,038 ha) and 20% of the total crop production volume (~413,652,648 t). It ranked among the top three main crops in each of the countries.
- **Wheat is the second most important crop across countries**, with 12% cultivated area (~38,729,676 ha) and 6% crop production volume (~125,876,873 t). India and Pakistan are among the top producers of wheat out of the eight countries.
- **Sugarcane is another prominent crop produced in large volumes,** particularly in India, Pakistan and Thailand. It ranks among the top five crops in all eight countries by total production volume. Due to high biomass production, sugarcane forms 29% (~593,001,814 t) of the total production volume in all countries with only 2% (~8,022,937 ha) cumulative cultivation area. The large volume of biomass production indicates very high residual biomass production as well, in the form of trash and bagasse.
- **Maize is a fourth key staple crop in these regions,** comprising 6% of the cultivation area and 4% of the production volume in the eight countries. It is the fourth main crop in Bangladesh, Cambodia, Indonesia and Pakistan, and fifth in Thailand and Vietnam. India has the largest absolute area under maize, but ranks seventh in total production volume.
- Other crops that have a significant share in the cultivation area and production volumes are **cassava** (with largest production volumes in Indonesia and Thailand), **potatoes** (with largest production volumes in India, Bangladesh and Pakistan), **oil palm** (only large in Indonesia), **bananas** (large in India, Indonesia, Thailand and Vietnam), and **mangoes** and **guava** (significant volumes in India, Bangladesh, Indonesia, Pakistan and Bangladesh).
- Among the eight countries, **India is the largest country, with a diverse climate, and as a result, the largest crop production volumes for almost all the top crops.** Sri Lanka is at the opposite end of the spectrum, with rice the largest crop produced, but a comparatively low one million hectares under cultivation.
- **A rich variety of vegetables and fruits is also grown in these regions** such as sweet potatoes, pumpkins, green beans, tomatoes, papayas, watermelons and citrus fruits (mandarins, oranges, grapefruits). However, it is difficult to determine the residual biomass and composition for these varieties, thus, they are not considered as potential feedstock for textile fibres for this assessment.

Following this, the technical potential of the top 20 crops from all eight countries was calculated, to understand the absolute maximum amount of residual biomass potentially available in the field (for primary residues) or at the processing mill (for secondary residues).

From Table 3.1, it can be seen that:

- **The largest volume of primary residues come from rice**, amounting to more than 600 million

Table 3.1: *Primary and secondary residues, and technical potential for the crops on the longlist*

Crop	Production main product in 8 countries (in tonnes, t)	Residue type	Description	RPR*	Total technical residue potential (t dm)
Sugarcane	593,001,814	Trash	Field residue, leaves & tops	0.14	83,020,254
	593,001,814	Bagasse	Pressed sugarcane, effluent	0.14	83,020,254
Rice	413,652,648	Straw	Field residue, stalks	1.25	517,065,810
	413,652,648	Husk or hulls	Coating on a grain of rice	0.28	115,822,741
Wheat	125,876,873	Straw	Field residue, stalks	0.85	106,995,342
	125,876,873	Bran	Coating on a grain of wheat	0.2	25,175,375
Oil, palm fruit (fresh bunch)	230,420,117	Fronds	Leaves & petiole	1.2	276,504,140
	230,420,117	Petiole		0.05	11,521,006
	230,420,117	Empty fruit bunch	Bunch after removal of oilseeds	0.19	43,779,822
	230,420,117	Oil palm shell	Coating of kernel	0.08	18,203,189
	230,420,117	Oil palm mesocarp fibre	Palm press fibre	0.21	48,388,225
Maize	78,423,490	Stover	Stalks and leaves	0.5	39,211,745
	78,423,490	Maize cobs	What remains after removal of grains	0.5	39,211,745
Cassava	70,264,241	Cassava stalk	Stalks and leaves	0.2	14,052,848
	70,264,241	Peels	Peels from root	0.1	7,026,424
	70,264,241	Fibre from starch extraction	Fibres in root after extraction of starch	0.17	11,944,921

Crop	Production main product in 8 countries (in tonnes, t)	Residue type	Description	RPR*	Total technical residue potential (t dm)
Bananas + Plantains**	42,967,055	Banana fronts	Leaves	0.14	6,015,388
	42,967,055	Pseudo-stems /trunk	Trunk after cleaning plantation	0.15**	6,445,058
	42,967,055	Inflorescent		1	42,967,055
	42,967,055	Rejected fruit		0.15	6,445,058
Coconuts	35,888,245	Coconut husk	Husk around the coconut	0.6	21,532,947
		Copra cake	Remains after oil extraction from copra	0.1	3,588,825
		Coconut shell	Shell of coconut after removal of milk and cocos	0.5	17,944,123
Mangoes, mangosteens and guavas	33,789,591	Woody prunings	Orchard residues from pruning	0.1	3,378,959
	33,789,591	Mango peels	Fruit peels	0.15	5,068,439
Tomatoes	21,500,464	Stalks and leaves		0.1	2,150,046
Seed cotton	19,546,231	Cotton stalks		3.5	68,411,809
	19,546,231	Linter		0.03	586,387
Soy beans	15,148,147	Straw	Stalks and leaves	2.5	37,870,368
Citrus fruits (oranges, tangerines, mandarins, lemons, grape fruit)	18,888,588	Woody prun-ings	Orchard residues	0.1	1,888,858
		Pulp (skin)		0.3	5,666,576
		Pulp (from juice indus-try)		0.15	2,833,288

Crop	Production main product in 8 countries (in tonnes, t)	Residue type	Description	RPR*	Total technical residue potential (t dm)
Millet	12,014,153	Straw	Stalks	1	12,014,153
Rubber, natural	10,601,870	Old trees after replanting		0.1	1,060,187
Rapeseed	9,042,060	Stalks		1	9,042,060
Groundnuts, with shell	7,852,501	Groundnut shells		2.5	19,631,252
Papayas	7,191,433	Woody prunings	Orchard residues	0.1	719,143
Pineapple***	6,547,762	Leaves		0.25	1,636,941
Okra****	6,246,637	Stalks		0.28	1,749,058
Sorghum	4,983,142	Stalks and leaves		2.62	13,055,832
Sweet pota-toes	4,927,062	Leave and vines		0.5	2,463,531
Coffee	2,705,260	Coffee silver-skin		0.042	113,621
	2,705,260	Coffee husk/ pulp		2.13	5,762,204
	2,705,260	Spend coffee grounds		0.65	1,758,419

* RPR, or residue to product ratio indicates the ratio between main crop product (e.g., grains, sugarcane) and the amount of residue (e.g., straw, trash) in kg dry matter (dm) per tonne. Several sources were used to derive the RPR ratios and typical moisture levels for these residues, particularly, OECD/IEA (2010) and Feedipedia . These were fine-tuned with observations and measurements of WUR projects all over the world. Three examples of how the RPR was calculated are:

** Per tonne of bananas harvested, 4 tonnes of residues remain. These consists for 75% of pseudo-stem. The moisture content of the pseu-do-stem is 95%. This implies that the RPR= 4* 0.75 *0.05 = 0.15

*** Per tonne of pineapple harvested, 1.6 tonnes of pineapple leaves remain. These leaves have a moisture content of 85%. This implies that the RPR = 1.6*0.15= 0.25

**** Per tonne of okra beans harvested, 1.25 tons of residues remain (IEA, 2010). These residues consist of leaves and stems. However, the fibres come from the stem. Residues consist for 50% of stems with a moisture content of 65%. This implies that the RPR = 1.6*0.5*0.35= 0.28

tonnes of dry mass straw and rice husk in the eight countries combined.

- **The second largest amount of residue comes from oil palm,** as this crop produces large volumes of different residues of which the palm fronds (in the field) and the palm press fibre and the empty fruit bunches (in the oil palm mill) are most abundant. Every year, palm oil residues amount to at least 400 million tonnes of dry mass material in the focus regions, especially in Indonesia.
- **The third largest residue volume comes from sugarcane,** consisting of trash and bagasse, of which 160 million tonnes of dry mass material is produced per year and this production is most strongly found in India, Pakistan and Thailand.
- **Finally, the volume of straws of wheat and maize is also very large** in the focus regions, reaching a technical dry mass potential per year of at least 200 million tonnes of straw.

After determining the annual amount of residual biomass produced for the longlisted crops in these countries, the next stage was to calculate the total cellulose and fibre content and related volumes. High cellulose content is a critical condition to extract cellulose from these residues and produce cellulose-based textile fibres. The threshold value for high cellulose was set at greater than or equal to 30% (see Table A1.4 in Annexure 1). It was found that sugarcane trash and bagasse; rice straw, husks and hulls; wheat straw; oil palm fronds, petioles and empty fruit bunches; maize stover and cobs; soybean straw; and, sorghum stalks were among the crop residues with cellulose values >=30%, thus, making them feasible for cellulose extraction.

In addition, the longlisted crops were assessed on the basis of the degree of polymerization (DP), their crop family, and if there is scientific evidence demonstrating their utility as a agricultural fibre. Using these criteria (see Table A1.4 in Annexure 1), the crop residues with the highest suitability for fibre extraction for textiles were found to be banana pseudo-stems and fronds; pineapple leaves; okra stems; and, coconut husk. Out of these, residues from okra and coconut are found to produce textiles of low quality and hence these were not shortlisted.

While there are several crops from which cellulose can be extracted, these were not shortlisted due to a number of reasons, including a relatively small technical potential in a given region; ideally, a minimum of over one million tonnes of dry matter (dm) should be available. But keeping in mind the small size of fibre extraction plants, the minimum availability of residues was set at a lower threshold than for cellulose extraction. Table 3.2 shows the shortlist of selected crop residues for textile fibre extraction.

Note: Cotton stalks and linter are also technically viable agro-residues. However, these were not shortlisted as they are derived from cotton crop, which is already the most important and widely used feedstock in the textile industry. This study aims to highlight other viable agro-residue based sources that can be used as textile fibre feedstock. Presently, linter is used to make cupro and has industrial and medical purposes, while cotton stalks are viable bio-energy sources and alternative for conventionally wood-based products like particle boards. The existing cotton-sourcing and logistical value chains should be taken into account when assessing the viability of these residues.

Table 3.2: *Shortlist of selected crop residues from each of the eight countries*

Crop	Residue type	Country	For cellulose or fibre?
Sugarcane	Trash	India	Cellulose
Sugarcane	Trash	Thailand	Cellulose
Sugarcane	Bagasse	India	Cellulose
Sugarcane	Bagasse	Thailand	Cellulose
Sugarcane	Trash	Pakistan	Cellulose
Sugarcane	Bagasse	Pakistan	Cellulose
Rice	Straw	Bangladesh	Cellulose
Rice	Straw	Cambodia	Cellulose
Rice	Straw	India	Cellulose
Rice	Straw	Indonesia	Cellulose
Rice	Straw	Pakistan	Cellulose
Rice	Straw	Sri Lanka	Cellulose
Rice	Straw	Thailand	Cellulose
Rice	Straw	Vietnam	Cellulose
Wheat	Straw	India	Cellulose
Wheat	Straw	Pakistan	Cellulose
Sorghum	Stalks/straw	India	Cellulose
Oil palm	Empty fruit bunch	Indonesia	Cellulose
Oil palm	Empty fruit bunch	Thailand	Cellulose
Maize	Stover/straw	India	Cellulose
Maize	Stover/straw	Indonesia	Cellulose
Banana and plantain	Banana fronts (leaves)	India	Fibre
Banana and plantain	Pseudo-stem/trunk	India	Fibre
Pineapple	Leaves	India	Fibre
Pineapple	Leaves	Indonesia	Fibre
Pineapple	Leaves	Thailand	Fibre
Pineapple	Leaves	Vietnam	Fibre

The last criterion used for final residue selection was the availability of a given residue in relation to its existing competing uses. This proved to be one of the most challenging criteria to assess due to incomplete information. The information on competing uses of the shortlisted crop residues was collated through extensive literature reviews, with the gaps filled in through interviews with regional agricultural experts (see Annexure 3). Using this, a classification of the availability of the unused residue potential (high, medium and low) was made.
Further narrowing of the above shortlist was based on two factors: low levels of competing uses for the residue, and a relatively even spread of hub locations across the eight study countries. Table 3.3 shows the final selection of crop residues that can be sourced from each focal country.

Note: While empty fruit bunches (EFBs) from oil palm are secondary residues, i.e., sourced directly from processing mills, and are technically feasible cellulose-based raw materials to produce textile fibres, it is important to take note of the challenges surrounding oil palm cultivation. The expansion oil palm cultivation has adversely affected tropical biodiversity, through widespread loss of rainforests and wildlife habitat, while also driving deforestation, fragmentation and degradation in natural forests (Astari and Lovett 2019; Azhar et al. 2017; Baron et al. 2017; Dharmawan et al. 2020). Several initiatives have been launched to improve the sustainability in oil palm cultivation, leading to the establishment of mandatory certification standards like RSPO (Carlson et al. 2018).
In principle, the option to use the EFBs from palm oil mills to produce textile fibres may help in improving the efficiency of this sector. However, it will be important to ensure that the EFBs come from sustainable plantations certified by bodies like the RSPO and FSC.

Table 3.3: *Final selection of crop residues per country*

Study regions	Residues possible
Bangladesh	Cellulose: Rice straw Fibre: Banana pseudo-stem
Cambodia	Cellulose: Rice straw
India	Cellulose: Rice straw, wheat straw, maize straw, sorghum straw, sugarcane trash and bagasse Fibre: Banana pseudo-stem and pineapple leaves
Indonesia	Cellulose: Rice straw, maize straw, oil palm EFB, sugarcane trash and bagasse Fibre: Banana pseudo-stem
Pakistan	Cellulose: Rice straw, wheat straw, maize straw, sugarcane trash and bagasse
Sri Lanka	Cellulose: Rice straw
Thailand	Cellulose: Rice straw, maize straw, oil palm EFB, sugarcane trash and bagasse Fibre: Banana pseudo-stem, pineapple leaves
Vietnam	Cellulose: Rice straw, maize straw Fibre: Banana pseudo-stem, pineapple leaves

3.2 Spatial analysis to identify hub locations from eight countries

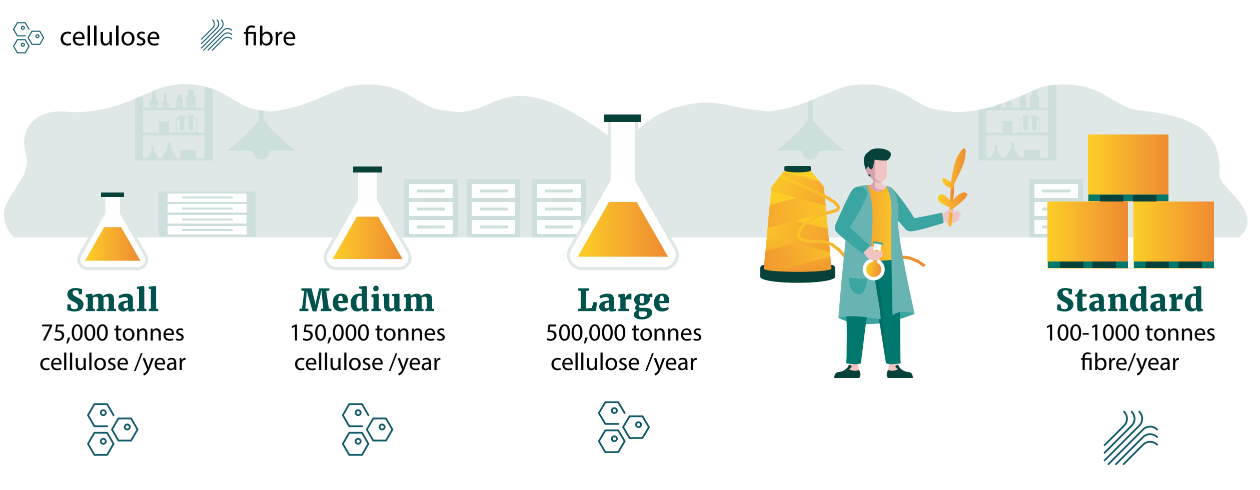
Following the final selection of crops (in Table 3.3), the spatial analysis was carried out to determine the hub locations in the most promising residue-country combinations for sourcing cellulose and fibres. These hubs indicate the presence of existing local infrastructure like transportation, processing facilities and proximity to nearby towns/cities that can be utilized and even expanded to accommodate the processing capacity required for the two routes, i.e., cellulose dissolution and fibre extraction. As the eight countries vary in size, more than two hub locations are investigated for the larger countries like India and Indonesia, and only one hub location is chosen for the smaller countries like Sri Lanka and Cambodia.

Additionally, different sizes of processing mills for both routes are also outlined for the different hub locations, keeping in mind the varying physical availability of residues in each country. While the availability of minimum of over one million tonnes dry matter (dm) biomass is the ideal criterion for setting up processing plants, in this analysis, the minimum threshold was lowered to suit the context of the eight countries.

Some key observations on sourcing and identifying hub locations from the spatial analysis are:

- Large hubs can be established in many locations, particularly for rice straw, for which sourcing biomass to produce 500 kilotons of cellulose per year is easy to do within a 100-km radius in countries like India, Bangladesh, Vietnam and Indonesia.
- In India, the large sourcing size can be met by combining rice straw with cereal straw, and in Indonesia, a combination of rice straw with maize stover can be used. In the other countries, combining straws is less attractive because the amount of production of straws other than rice are smaller and often, the cultivation fields for rice and other cereals do not coincide spatially.
- Large cellulose dissolving plants for sugarcane residues (trash and bagasse) can easily source a combination of trash and bagasse in India, even within a 50-km sourcing circle.
- In some countries, biomass sourcing for a small cellulose dissolving mill, i.e., a maximum of 75 kilotons of cellulose per year, is possible such as

Figure 3.1: *Sizes of mills for different processing routes*



rice straw in Sri Lanka and Pakistan, and sugarcane trash in Thailand and Pakistan.

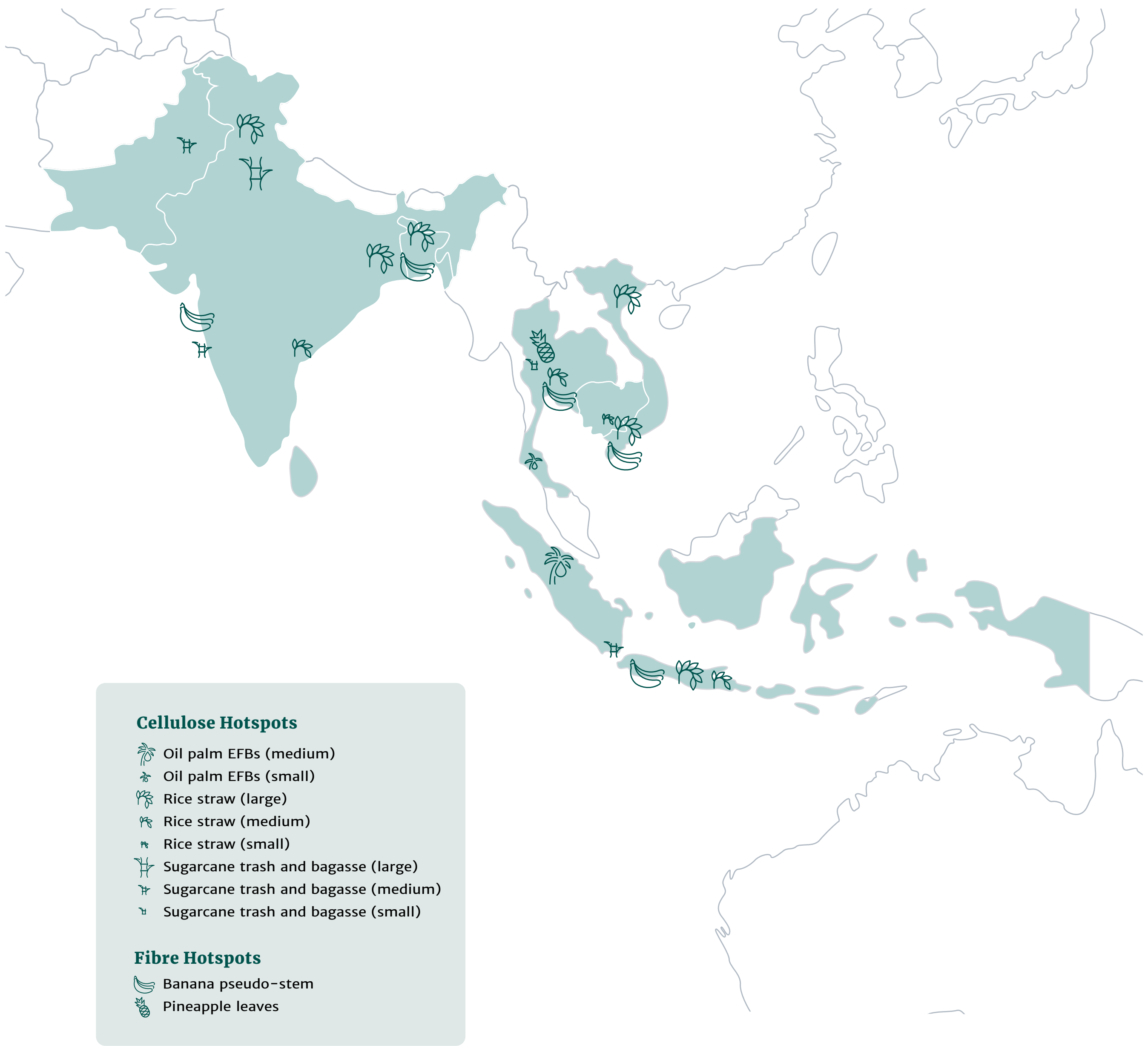
- Sourcing of empty fruit bunches (EFBs) from oil palm trees for cellulose dissolving and regenerating plants is only possible in Indonesia and Thailand, and is best suited for medium and small plants, respectively.
- For banana pseudo-stems and pineapple leaves, the most promising fibre sourcing regions are primarily found in India, Bangladesh, Thailand, Vietnam and Indonesia. These regions are best suited for cultivating these tropical crops and have the highest concentrations of their plantations.

An overview of all hub locations in eight countries is given in Map 3.1.

3.2.1 Rice straw and other cereal straws

As noted earlier, rice is one of the primary cereal crops cultivated among all eight countries, with the exception of Pakistan. This makes straw from rice one of the major large-scale crop residues potentially available for cellulose production for textiles. Rice straw is available in abundance and has limited competing uses (see Annexure 3). Although sometimes used as cattle fodder, rice has a slow decomposition rate and often, abundant leftover rice straw is burnt in the fields after harvesting. This is an easy, low-cost method of residue disposal and the clearing of fields for the next sowing season. Burning of rice straw is further driven by a lack of equipment and machinery in rice-growing regions that could harvest grains and remove straw simultaneously. Although mass burning is seen as an environmental threat, and prohibited by regulations in most countries[10], it remains the quickest and most effective method of managing abundant straw residues from rice crop.

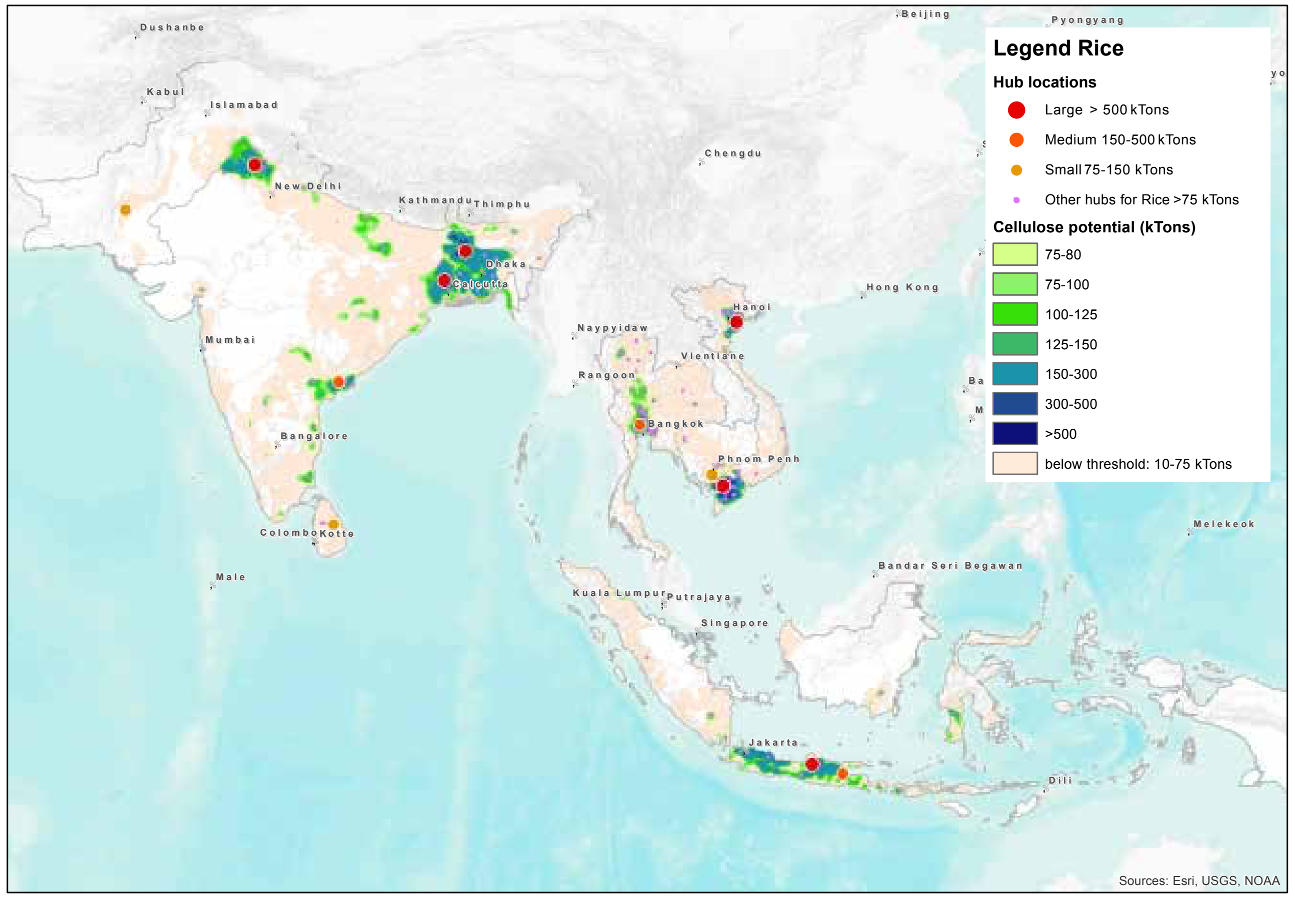
Map 3.1: *Final hub locations identified for vegetal cellulose and fibre sourcing (for region-specific locations, see also tables in Annexure 4)*



The distribution of rice production across the eight countries is shown in Map 3.2. The best hub locations coincide with the regions with the highest concentrations of rice production (see Table A4.2 in Annexure 4). This is particularly seen in Rajshahi, Bangladesh; Andhra Pradesh, Punjab and West Bengal, India; the island of Java, Indonesia; and in the Thái Bình and An Giang regions of Vietnam.

10 Increasingly, countries are prohibiting and penalising the burning of residues through legislative or regulatory actions such as India, Thailand and Indonesia in South and Southeast Asia, along with other countries like China and Russia.

Map 3.2: *Cellulose potential from rice straw in the eight focus countries and hub locations for sourcing small, medium and large-scale cellulose extraction plants within a 100-km radius.*



Combination with other cereal straws

The combination of rice straw with other cereal straws like wheat, maize and sorghum were also analysed to explore options to securing a steady supply of straws to the cellulose dissolving plants. An example of this can be found in the Punjab region in India, where rice and wheat are cultivated in a rotation on the same fields, with the production of wheat being the largest (see Map 3.3). An entire chain relying only on cereal straws as textile feedstock was not examined, as there are several competing uses for cereal straws such as cattle feed, bedding and other material uses, vis-à-vis rice straw. This also increases the price of cereal straws. While cereal straws are also burnt, their burning happens on a much smaller scale as compared to rice straws.

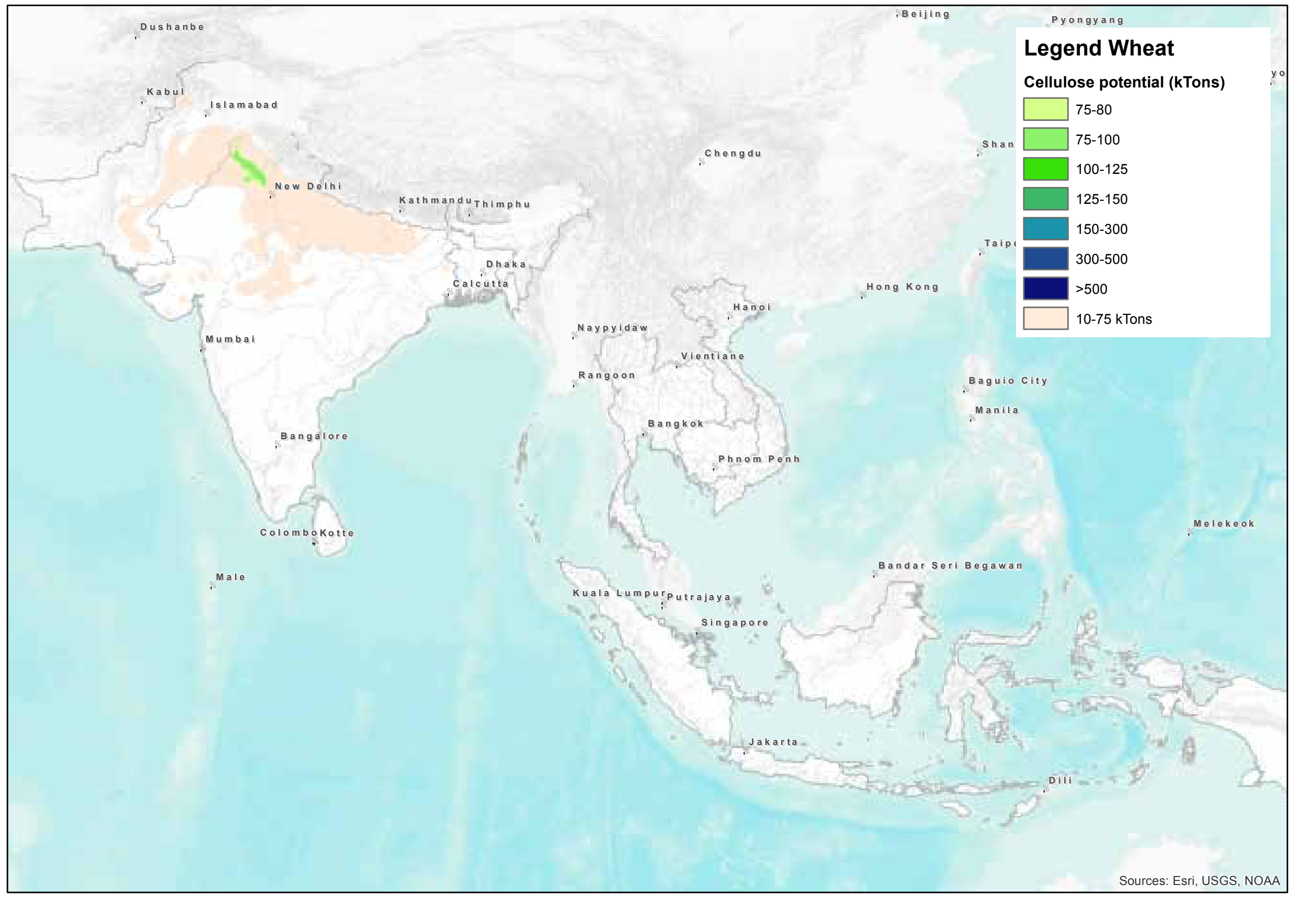
3.2.2 Sugarcane trash and bagasse

Sugarcane is most widely cultivated in India, which is the largest global producer of sugarcane in the world after Brazil. Pakistan, Thailand and Indonesia also grow sugarcane but at a much smaller scale. As a result, in India it is feasible to source from locations where a large amount of sugarcane trash and/or bagasse is available to feed into a large cellulose dissolving and regeneration plant with 500,000 tonnes of annual capacity (see Map 3.4). In the other countries, only small and medium-sized processing plants are feasible. Trash and bagasse are the two main residues from sugarcane crops.

Sugarcane trash

Trash is a primary residue available on the field, and consists of the tops and leaves of the sugarcane. The average RPR for sugarcane is 14%, which means that large amount of trash is produced per hectare of sugarcane crop. For every tonne of sugarcane harvested, 12-16% of trash is technically available on the field. For example, if the average annual yield per hectare of sugarcane is 80 tonnes, then about 10 tonnes dm is available annually per hectare on an average. But it is important to note that this reflects only the technical potential of the residual biomass

Map 3.3: *Wheat production in the eight focus countries*



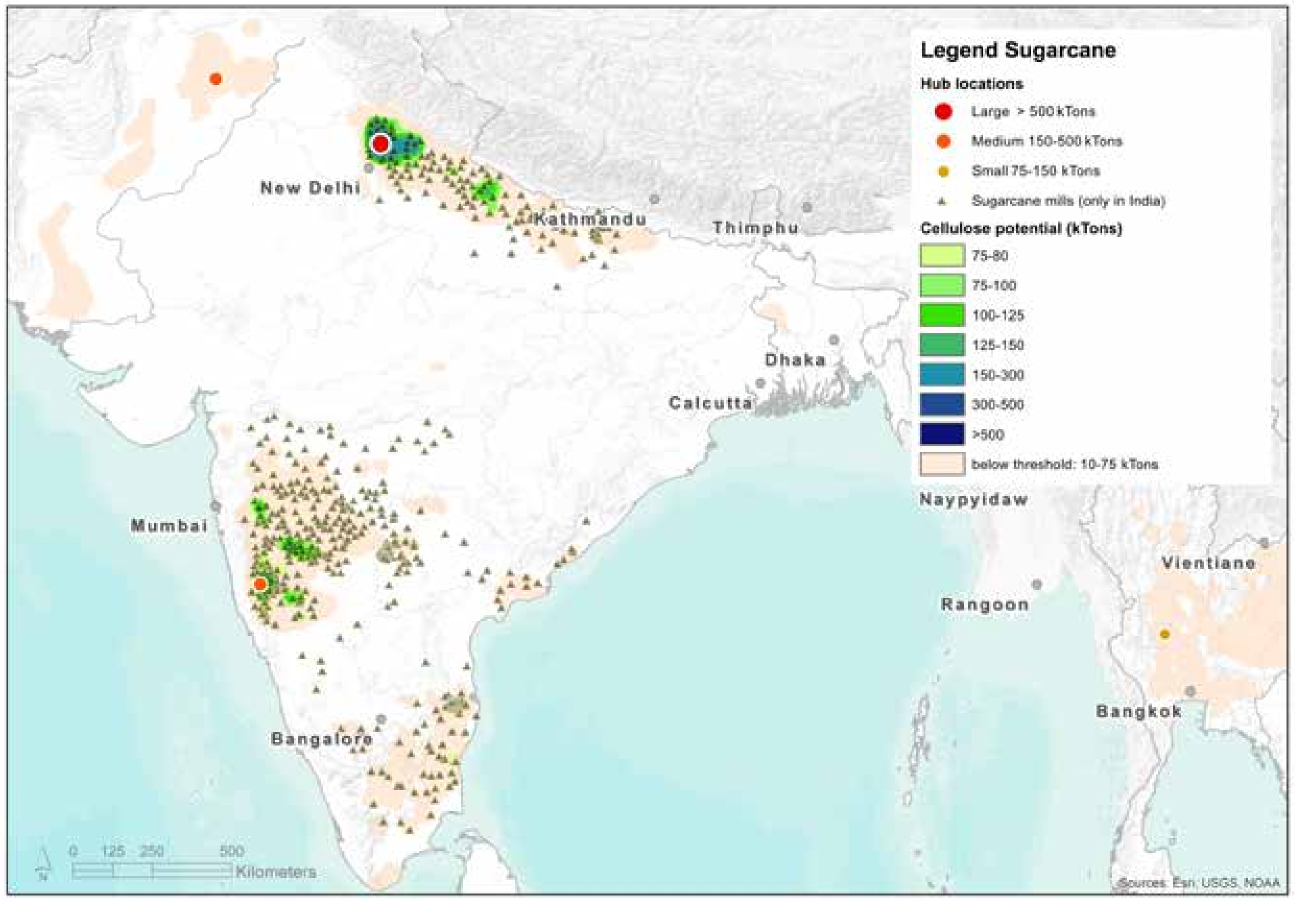
(Kumar et al. 2017; Jain et al. 2014). Sustainable removal rates necessary to maintain soil nutrients as much as possible, are likely to be much lower.

The use of sugarcane trash is very limited, with an estimated 25% being burnt on the field (Jain et al. 2014). A study on 10 Indian states producing sugarcane found that about 3 tonnes of trash is mulched for conserving soil moisture and nutrients, about 30% is transported to the sugar mill with the crop, and only 40% of the trash remains, most of which is burnt on the field (Kumar et al. 2017). About 28 million tonnes of unutilised trash is left on the field and can be used for cellulose extraction. Out of this, about 13 million tonnes is available in the state of Uttar Pradesh, India (see Annexure 3).

Sugarcane bagasse

Bagasse, the other residue from sugarcane, is an example of secondary residue found in sugar mills. In India, there are about 600 sugar mills in operation that process over 200 million tonnes of sugarcane annually, and this generates about 75-90 million tonnes of bagasse with 40% moisture content (Qureshi et al. 2020). Bagasse has a major competing use as a fuel, due to its high caloric value (8021 kJ.kg) and is used in boilers to generate steam and electricity within the sugar mills. Other applications include use as a raw material in agro-residue-based pulp and paper mills. It is not possible to source all the bagasse available in sugar mills as it forms a key fuel source for the mill. Its replacement will result in a higher dependency on other energy sources like fossil fuels, which could adversely affect the greenhouse gas (GHG) balance of sugar mills. Map 3.4 shows the hub locations for sourcing sugarcane residues (trash and bagasse) for cellulose extraction and their capacities. It also maps the sugar mill locations for India. Mill locations for other countries like Pakistan, Thailand and Bangladesh could not be mapped due to unavailability of data.

Map 3.4: *Cellulose potential from sugarcane residues and hub locations for sourcing small-, medium- and large-scale cellulose extraction plants within a 100-km radius (Note: Sugar mill location are only mapped for India, for other countries no locational data were identified)*



3.2.3 Empty fruit bunches (EFBs) from oil palm

Empty fruit bunches (EFBs) are an example of secondary residues from oil palms. After the extraction of palm oil from fresh fruit bunches, EFBs are left behind in the palm oil mills and form very bulky residues with high moisture content. In addition to cellulose, these residues contain highly lignified spikes, and their fibre bundles are covered in silica bodies.

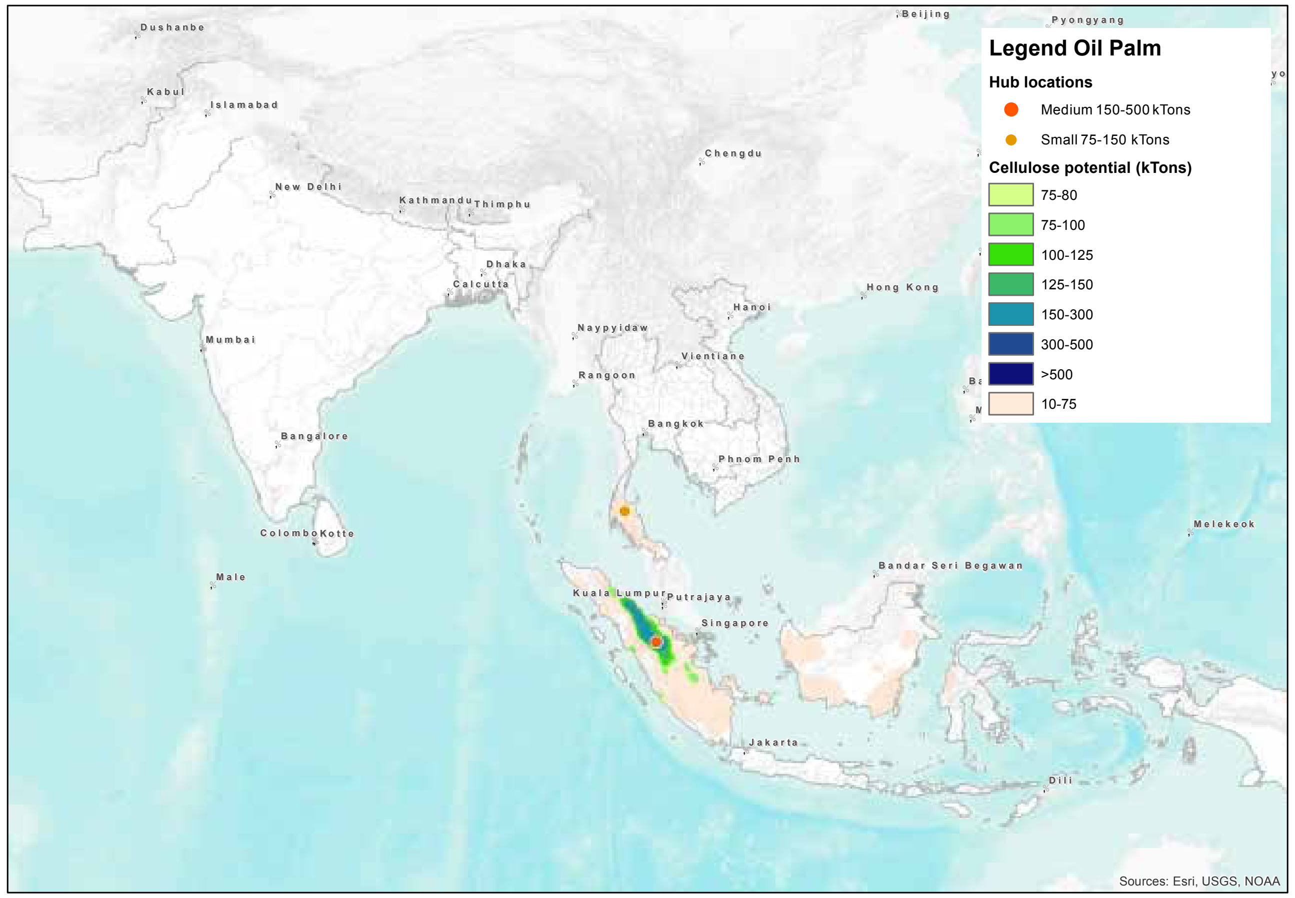
As secondary residues, EFBs do not presently have many competing uses. If not left as waste or burnt (without energy recovery), EFBs are generally mulched and returned to the field. There may be real opportunities to find other applications that offer additional revenue streams, even while combating issues like environmental degradation, air pollution and GHG emissions arising from the burning of these residues.
Among the eight countries, Thailand and Indonesia stand out as the largest producers of oil palm. These countries can provide sourcing hubs to support both small and medium cellulose processing plants with 75 kilotons and 150 kilotons cellulose pulp per year, respectively (see Maps 3.5 and 3.6).

3.2.4 Banana pseudo-stems and Pineapple leaves

Out of the crop residues assessed for the fibre extraction route, only primary, field-based residues were considered that are not primarily produced for fibre extraction, but have reasonable quality of fibres known to be extracted at small-scale factories. Banana pseudo-stems and pineapple leaves stood out among the other crop residues, since their fibres can produce high quality textiles (see previous chapters). While okra leaves and coir from coconut were also considered initially, they were eliminated because fibres extracted from them are rough and not suitable for most apparel uses.

Banana pseudo-stems and pineapple leaves are currently under-utilized (see Annexure 3). In some regions of the world, fibres from banana and pineapple are already being used to produce textiles at a small scale. It is estimated that about 200 kilotons of banana-based fibres and almost 14 million tonnes of pineapple-based fibres are produced globally (Dunne et al. 2016). Residues from banana and pineapple trees are also often left in the field as a rich nutrient source; however, excessive residues may contribute to increases in pest attacks as well.

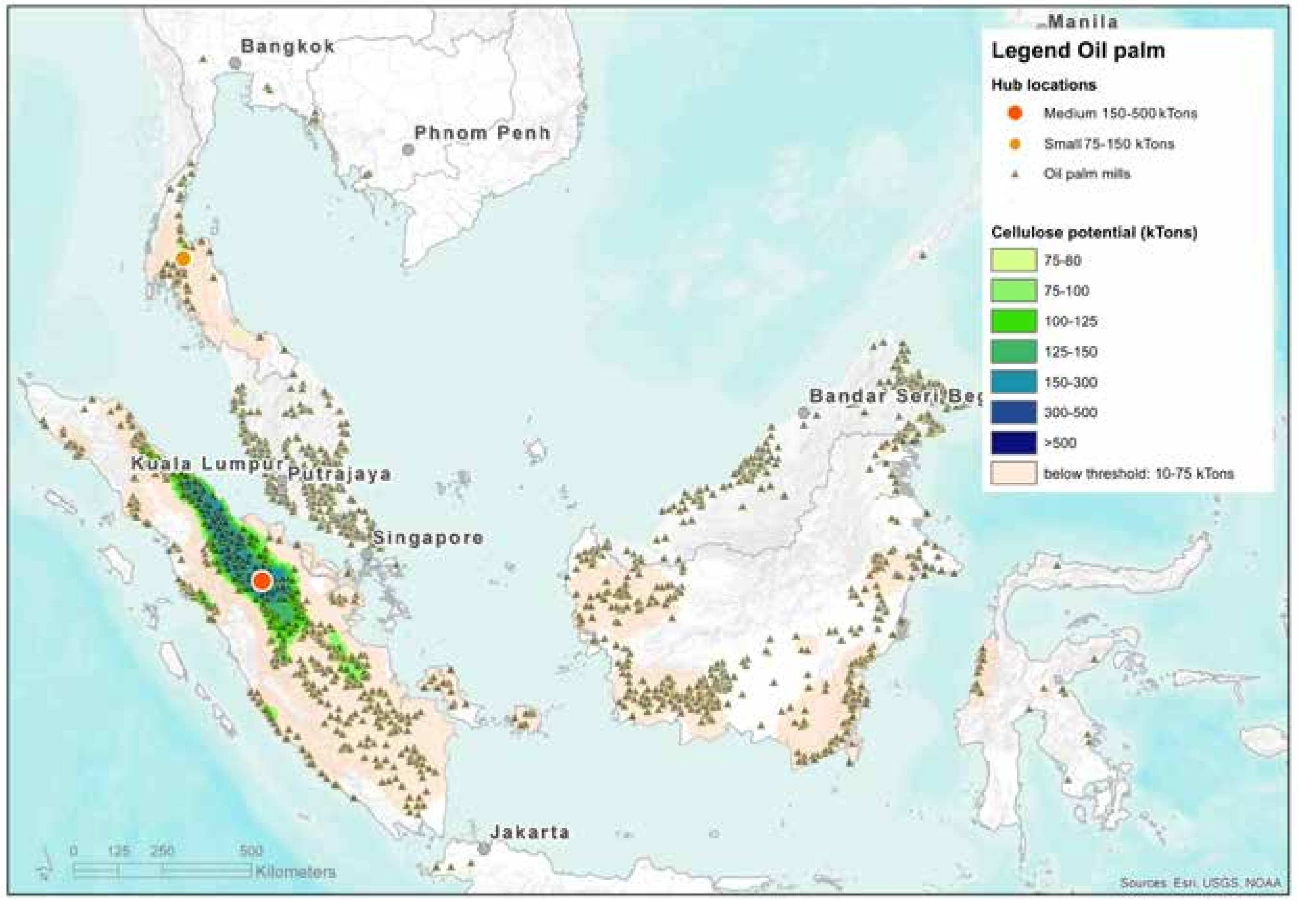
Map 3.5: *Oil palm production in study regions and possible hub locations for a cellulose dissolving plant*



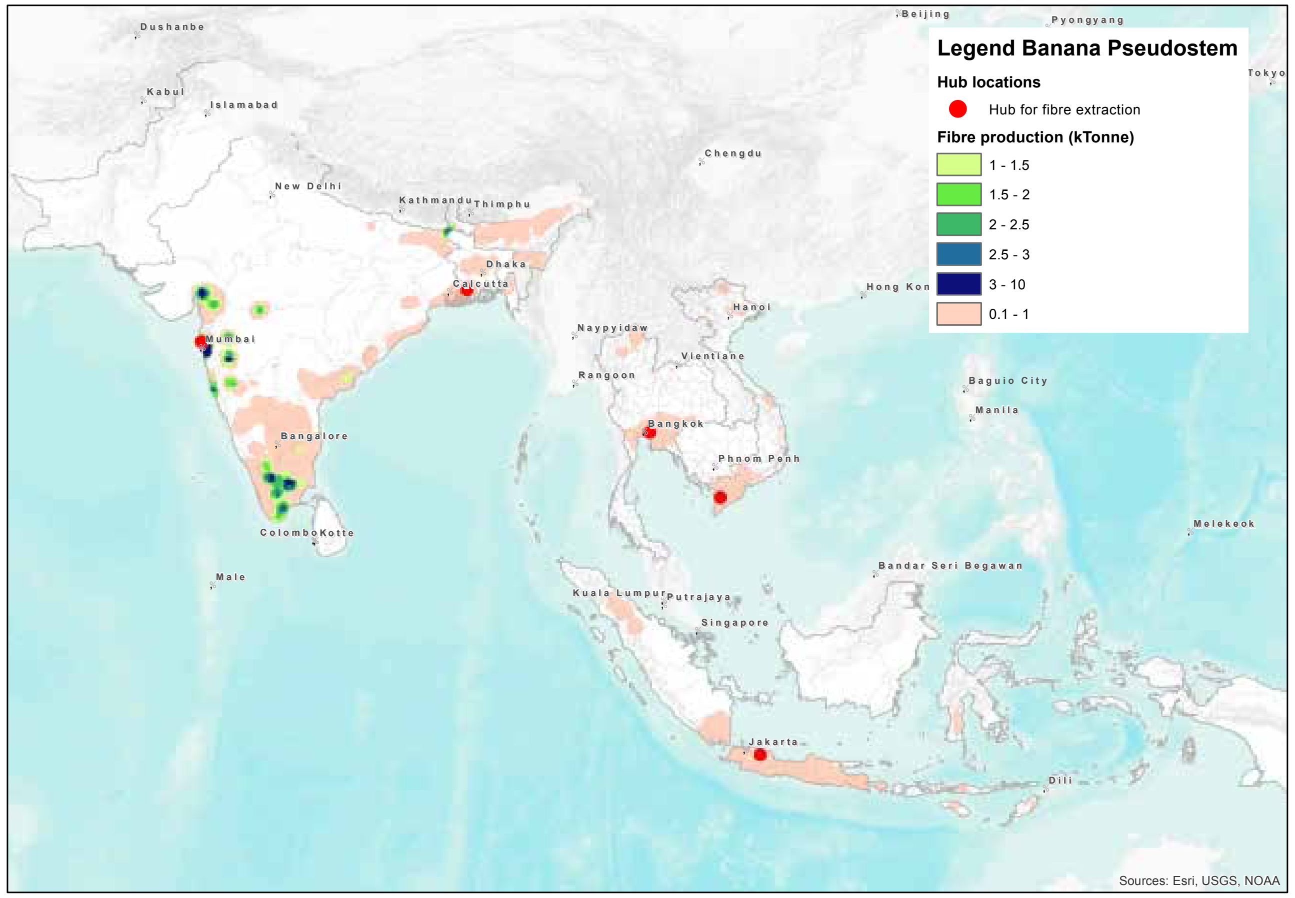
In the spatial assessment for banana pseudo-stems and pineapple leaves, the annual factory fibre output capacity was assumed to be 100-1000 tonnes per year. Accordingly, the quantity of feedstock was calculated on this basis and hub locations were identified.

Maps 3.7 and 3.8 show the distribution of these crops and their related fibre potentials. Banana is produced widely in all eight countries, but in India, particularly in the regions of Tamil Nadu, Gujarat, Maharashtra and Bihar, the size and concentration of the banana production is significantly large, which makes these locations highly promising. On the other hand, areas of pineapple production are less widespread than for banana. Thailand has the largest and most densely concentrated production of pineapple among the eight countries. For the cost analysis, hub locations for sourcing banana fibres are evaluated in India, Bangladesh, Thailand, Vietnam and Indonesia, which have very different banana plantation densities (see Annexure 5).

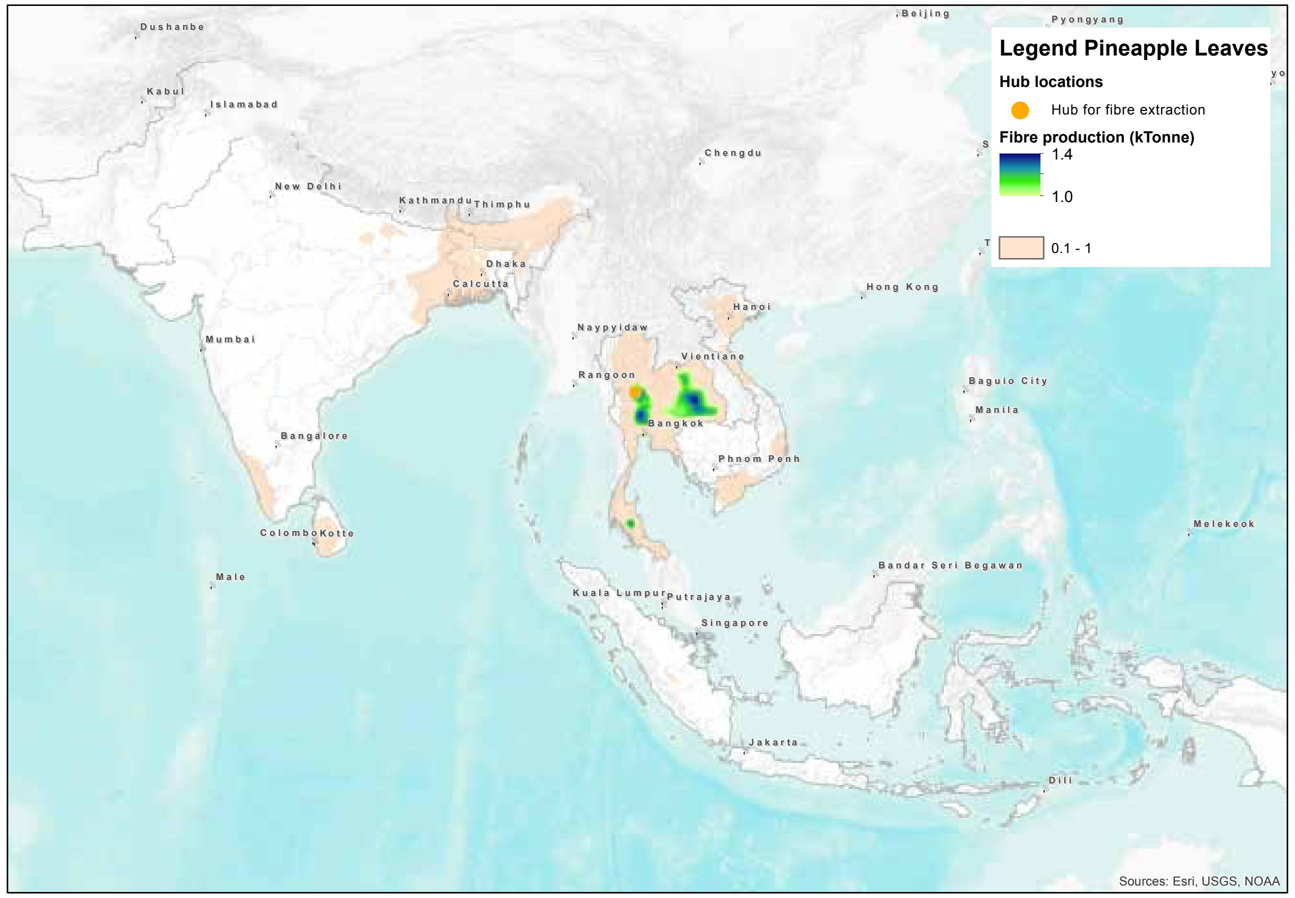
Map 3.6: *Locations of palm oil mills in Indonesia and Thailand from which the EFB residues can be sourced to cellulose dissolving mills and possible hub locations*



Map 3.7: *Fibre potential from banana pseudo-stem in the eight focus countries, and selected hub locations*



Map 3.8: *Fibre potential from pineapple leaves in the eight focus countries, and selected hub locations*



4

Pre-feasibility and Viability Considerations

4 Pre-feasibility and Viability Considerations

4.1 Value chain design and assumptions for cost assessment

The selected crop residues listed in Table 3.3 exhibit diverse characteristics, such as varying cellulose, fibre and moisture contents, that affect costs associated with their sourcing and delivery including transportation, labour, energy and pre-processing.

Some residues, like banana pseudo-stems, pineapple leaves, sugarcane bagasse and oil palm EFBs, have very high moisture content. As a result, transporting these residues to cellulose dissolving or fibre extractions plants can be inefficient. While pre-processing treatments like drying and densification can make their transportation easier, these would add higher energy and handling costs, and have not been considered in this assessment's cost calculations.

For residues like rice straw and sugarcane trash a densification step was considered at an intermediate collection point, or ICT (see Figure 4.1), where the residues are converted into pellets to increase bulk density from 150 kg/m3 to about 600 kg/m^3. This pelletising process adds additional cost (for details, see Annexure 5) to the delivery of the biomass to the processing plant. However, this additional cost may be partially or fully compensated by the lower overall transportation costs which is shown in the results. The alternative is to transport the loose straw or trash bales, that have much lower bulk density but are more expensive to transport, straight from the field to the cellulose dissolving plant. The long-distance transportation costs become higher for these bales, but the costs for densification into pellets are not incurred in this option (see Chain 3 in Figure 4.1). The cost calculation exercise will determine the efficacy of these scenarios (see Section 4.2 for cost calculations).

In addition to the densification costs, the pre-processing stage at the ICT will also involve additional costs such as labour costs for off-loading and uploading. There may also be a possibility of storing the biomass at the ICP in case it cannot be delivered year-round to the cellulose dissolving (CD) plant. Storage can also be done at the CD plant if there is no ICP plant involved in the delivery chain.

Note: The complete effect of densification of the biomass on the cellulose extraction process is unknown. A higher degree of densification may influence the quality of the cellulose. This requires further review.

Table 4.1: *Summary of value chain design and cost assumptions per selected biomass type*

	Agricultural residues for cellulose dissolving plant				Agricultural residues for fibre extraction plant	
Biomass type	**Rice straw (combined with cereal straw in Punjab, India)**	**Sugarcane trash**	**Sugarcane bagasse**	**Empty fruit bunch (EFB) of oil palm**	**Banana-pseudostem**	**Pineapple leaves**
Field (primary) or Mill (secondary) residue	Field residue	Field residue	Mill residue	Mill residue	Field residue	Field residue
Cellulose and fibre content (kg cellulose/tonne dry residue mass)	380 kg cellulose/ tonne dry straw	340 kg cellulose/ tonne dry trash	460 kg cellulose/ tonne dry bagasse	410 kg cellulose/ tonne dry EFB	20 kg fibre/ tonne dry pseudo-stem	100 kg fibre/ tonne dry pineapple leaves
Average moisture content after harvest or at mill	14%	14%	40%	50%	95%	70%
Storage assumptions	3 months	3 months	No storage needed	No storage needed	No storage needed.	No storage needed.
Chain designs applied (see Fig 4.1)	Chains 1 and 3	Chains 1 and 3	Chain 2	Chain 2	Chain 3	Chain 3
Contractibility levels assumed	Costs are calculated for two contractibility levels of technical potential: 60% 30%	Costs are calculated for two contractibility levels of technical potential: 60% 30%	Maximum 20% of the bagasse produced per sugar mill is available for cellulose extraction.	Costs are calculated for two contractibility levels of technical potential: 60% 30%	Costs are calculated for three contractibility levels of technical potential: 100% 60% 30% Higher contractability is possible if mill residues are returned to fields.	Costs are calculated for three contractibility levels of technical potential: 100% 60% 30% Higher contractability is possible if mill residues are returned to fields.

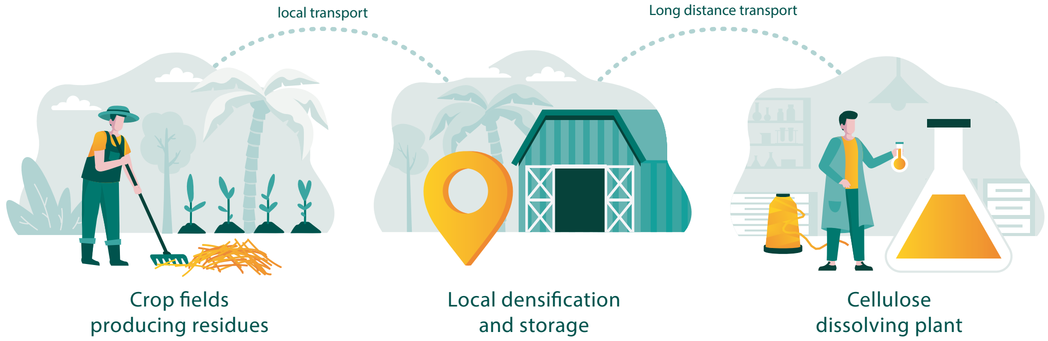
	Agricultural residues for cellulose dissolving plant				Agricultural residues for fibre extraction plant	
Biomass type	Rice straw (combined with cereal straw in Punjab, India)	Sugarcane trash	Sugarcane bagasse	Empty fruit bunch (EFB) of oil palm	Banana pseudostem	Pineapple leaves
Options for collection and pre-treatment of residue and associated transportation cost (USD/tonne/km)	1) Straw bales are transported from field to ICP* where pellets are made increasing bulk density from 150 kg/m^3 to about 600 kg/m3. 0.05 USD/tonne/km 2) No densification takes place and straw bales are transported directly to CD plant. 0.20 USD/tonne/km	1) Trash bales are transported from field to ICP* where pellets are made increasing bulk density from 150 kg/m3 to about 600 kg/m3. 0.05 USD/tonne/km 2) No densification takes place trash bales are transported directly to CD plant 0.20 USD/tonne/km	Bagasse is collected at the sugar mills into a large lorry and transported directly to the CD plant. 0.05 USD/tonne/km	Collection at the oil palm mills, direct transportation to the CD plant with large lorries. 0.05 USD/tonne/km	1) Only outer pseudo-stem is removed from field. 2) Whole pseudo-stem is removed from field. In both cases, direct transport from the field to fibre extraction plant. After fibre extraction, remaining residues are returned to fields. 0.20 USD/tonne/km	Leaves are collected from the field and transported directly to fibre extraction plant. After fibre extraction remaining residues are returned to fields. 0.20 USD/tonne/km
Purchase cost (see Annexure 5 for a detailed explanation of the costs involved)	A market price is assumed per tonne of dry straw and a compensation cost for removal of nutrients (NPK).	A market price is assumed per tonne of dry residue and a compensation cost for removal of nutrients (NPK) is allocated.	A market price is assumed per tonne of dry residue.	A market price is assumed per tonne of dry residue.	A purchase cost level of 0.05 USD/kg of fibre contained in the residual biomass is assumed.	A purchase cost level of 0.05 USD/kg of fibre contained in the residual biomass is assumed.
Up- and off-loading cost	Up- and off-loading costs are allocated every time biomass needs to be transported from field to ICP, from ICP to CD plant and at CD plant. Up- and off-loading costs are estimated at 0.5 USD per tonne biomass.					

ICP = Intermediate collection point. These are always located a maximum of 4 kms from the fields.
CD plant = Cellulose dissolving plant

Figure 4.1: *The three value chain designs considered for the delivery of biomass to the processing plant*

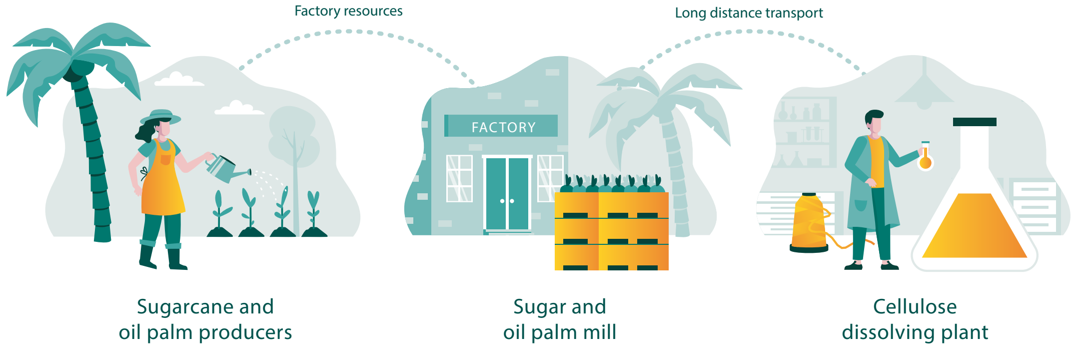
Chain 1: Local hub storage

Field residue biomass is harvested and baled in the field. After that, the bales are transported to an intermediate collection point within short distance of the fields (max. 4 km). Here, the biomass is densified (by making pellets) and stored before transport to a cellulose dissolving mill



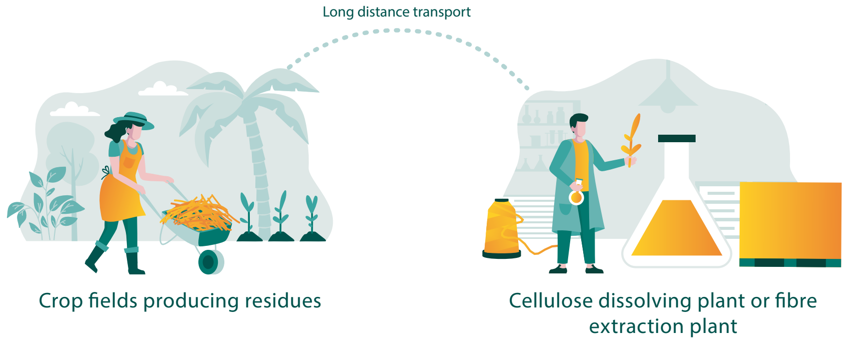
Chain 2: Factory to factory

The producers bring their crops to a mill for processing. The residue from the sugar factory and the oil palm mill is then collected, and transported in large lorries for long distance transport to the cellulose dissolving plant.



Chain 3: Farm to factory

The residues are collected and baled in the fields, after which they are transported directly to a cellulose dissolving plant or a fibre extraction plant.



For the cost assessment of the delivery chains, three major chain designs were considered (see Figure 4.1):

- **Chain design 1**, in which the field residue biomass is harvested and baled in the field and then transported to an intermediate collection point (ICP), located within a short distance of the fields (max. 4 kms), where the biomass can be densified into pellets and stored.
- **Chain design 2**, only applicable to secondary residues like sugarcane bagasse or oil palm EFBs. In this design, residues are collected at the sugar or oil palm mill respectively and transported by large lorries to the cellulose dissolving (CD) plant.
- **Chain design 3**, in which the residues are harvested and baled in the field and then directly transported for the CD or fibre extraction plant.

It should be noted that not all designs are applicable to all types of residual biomass (see Table 4.1 and Figure 4.1). Depending on the technology route (cellulose or fibre extraction) and factors like bulk density and moisture content, as well as requirement for pre-processing, the three chain designs are allocated to different crop residues. These chain designs also involve varied cost considerations.

Box 4.1: Effect of the quality of rice straw on cellulose extraction

While it can be realistically assumed that rice straw is likely to be the largest unused crop residue in the eight focus countries, the extraction of cellulose is a challenge and remains to be proven commercially viable. This is primarily due to a high silica content in rice straw than other residues like wheat straw and sugarcane trash. MMCFs require cellulose pulps to be virtually free of silica.

Different rice varieties have varying degrees of silica content. Paddy rice, which is the dominant variety produced in most of Asia, has high silica content. Comparatively, the Basmati variety, grown in many regions in India, has lower silica levels. Further research is needed to understand ways of addressing high silica levels at the cellulose dissolution stage, and also to ascertain which rice varieties are most suitable as textile fibre feedstock.

Pre-processing requirements

In the case of straws from rice and cereals (wheat, maize and sorghum), and sugarcane trash, Chain Design 1 can be employed. These residues are harvested in the field when they are relatively dry (10-20% moisture), either by hand or by a combine, and formed into bales with a bulk density up to 150 kg/m3 (Bakker et al. 2013). These bales are transported by 1-2 tonne capacity vehicles (e.g., rickshaw vans, a tractor and trolley, or a mini-van) to the ICP, which is about 4 kms from the field. These vehicles can even transport bales further to a CD plant. The latter implies that the transportation distance of the bales could even reach 100 kms, if needed.

Banana pseudo-stems and pineapple leaves, which follow Chain Design 3, can also be transported from fields to fibre extraction plants using the same small vehicle type and capacity. This transportation mode will become costlier if the distances become too large. It should be noted that fibre extraction plants do not require very large facilities to reach optimal economies of scale, whereas for CD plants, scale may be much more important to make a good business case. As discussed earlier, rice straw chains can be made either entirely from rice straw, or in combination with other cereal straws. Particularly for Punjab in India, a chain with a combination of rice and wheat straw can be a feasible option as these crops are cultivated in a rotational manner. In this case, a large-scale mill for cellulose extraction can be established. In this combination, rice straw will be in higher proportion to wheat straw (say, in a 3:1 ratio) since wheat straw has a number of competing uses due to its better quality.

Purchase cost for biomass

There are two methods of determining the purchase cost of residual biomass:

- **In the first method, the actual market price paid for the biomass can be used to determine its purchase cost.** This may not be applicable for all residues, as they do not currently constitute a commodity sold in the market. Market prices usually exist for residues that have several competing uses such as wheat straw, rice straw, sugarcane trash and bagasse. However, these prices differ greatly between regions and also according to the season. Therefore, assuming an average market price for residues is not feasible.

- **In the second method, the residue is valued on the basis of its cellulose or fibre content; the higher the cellulose/fibre content, the greater the price paid for the biomass**. A review of prices paid for fibres showed that banana fibres were priced at 0.1-0.8 USD/kg and pineapple leaf fibres were priced at 0.05 USD/kg (Dunne et al. 2016). For this study's cost analysis, a purchase cost of 0.05 USD/kg for fibres contained in biomass is considered as a reasonable estimate for the initial cost calculations (see Table A5.1 in Annexure 5 to see how this assumption works for the different fibre sources). In the case of cellulose derived from vegetable sources, it is difficult to establish the purchase cost of the biomass due to the diversity in sources and their qualities. In this assessment, a rough market price is assumed for the residues.

For certain countries, the prices are higher because of known competing use levels. For example, in Vietnam, rice straw costs are known to have increased because of the increase in demand for rice straw to make cattle feed, produce compost fertilizer and cultivate mushrooms. As the purchase costs are highly uncertain and limited reliable information is available, the total delivery cost of biomass to the plant gate is calculated both with and without the purchase cost.

Nutrient compensation

The cost of compensating for potential nutrient loss is also considered in the purchase price. Removal of residues from fields leads to the removal of nutrients that may be used to maintain soil quality, and thus carry ecological value. These nutrients need to be replaced and replenished by adding manure or artificial (purchased) fertilizers to maintain soil quality. **Fertiliser-based compensation is applicable only for crop residues undergoing cellulose extraction, as the high intensity of processing in the cellulose extraction route makes it challenging to bring used residues back to the fields.** The cost of fertiliser compensation for residues processed through the cellulose extraction route was calculated using the content of the NPK minerals contained in the field residues (based on FAO 2005, for rice and cereal straw in India and on Suma et al. 2015, for sugarcane trash) (see Annexure 5).

By contrast, in the fibre extraction route, spent residues can be brought back to the fields and partially compensate for nutrient loss, due to the simplicity of processing and smaller scale. While this negates the need to include fertilizer costs, it necessitates the inclusion of return transportation costs to the fields. This is particularly applicable for banana pseudo-stems. It is important to return nutrients to the plantations in which bananas are cultivated, due to the high nutrient requirements of banana, specifically nitrogen, potassium and phosphorus.

In the case of pineapple leaves, also a fibre-based value chain, loss of nutrients caused by residue removal is a concern, but removal has greater benefits. If these residues are left on the field, planting new pineapple plants is not possible. Also, decaying pineapple leaves attract insects like stable flies that cause diseases in humans and livestock; thus, removal of dead pineapple leaves is a necessary sanitation measure. While return transportation cost to the field as a way of compensating nutrient loss is applicable in case of pineapple leaves, it is important to design proper processing techniques to convert these mill residues into compost (or fertilizers) along with outlining the right application methods. This is not considered in the cost calculations. However, similar to banana pseudo-stems, return transportation costs for pineapple leaves are included in the cost analysis.

Distance and Transportation

Small trucks and vehicles can be used at a cost level of 0.20 USD/tonne/km for short distance transportation and for all non-densified residues that are transported directly from the field to the cellulose and fibre extraction plants.

For long distance transportation, more efficient large lorries are expected to be used which are much cheaper at 0.050 USD/tonne/km. These larger lorries cannot be used for direct collection of residues from fields, as the road networks may not allow it. These lorries are only expected to be used for transportation from one ICT or mill location to the CD or fibre extraction plant (see Annexure 5).

4.2 Cost calculations and considerations

The final costs for at-gate delivery of the residual biomass from the fields are outlined using separate cost factors, which include:

I. Purchase cost of the biomass and compensation cost for nutrients lost in the field due to removal of residues
II. Densification cost, in the case of intermediate conversion to pellets before long distance transport
III. Storage cost, in the case biomass is not available year-round because of seasonality, and the need to ensure year-round operations for cellulose dissolving mills
IV. Transportation costs (including up- and off-loading), which can be local, short and long distance.

These factors and the assumptions outlined earlier were used to calculate the final at-gate delivery costs for the two residue processing routes -- cellulose dissolution and fibre extraction. The calculations are outlined in the subsequent sections.

4.2.1 At-gate delivery cost for cellulose biomass sources

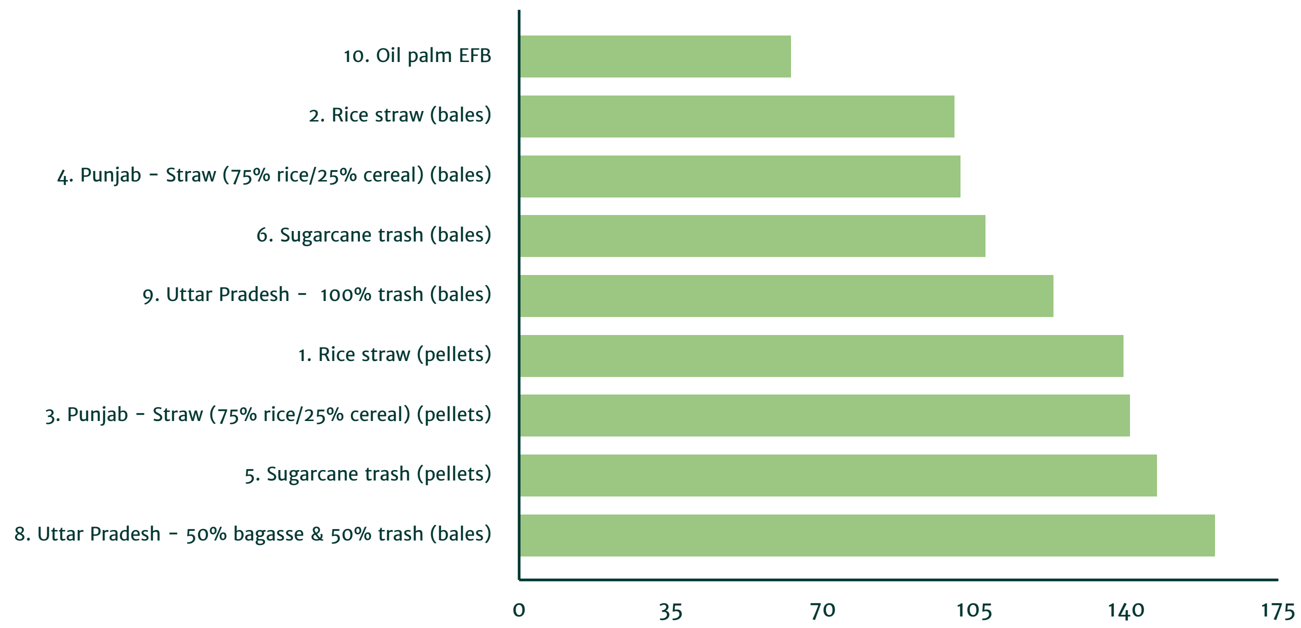
The total cost and detailed costs have been assessed for different sourcing combinations, with and without a densification step, and assuming 30% contractibility on average. Figure 4.2 presents the total average costs for sourcing in USD per tonne of cellulose. Table 4.2 shows the detailed cost levels and characteristics of the hub and chain combinations. The numbers of the hub chain combinations in Figure 4.2 correspond to the numbers in the first column of Table 4.2.

Among the various residue-country combinations:

- The lowest cellulose-based biomass delivery cost is for oil palm empty fruit bunches (EFB) at 63 USD/tonne of cellulose.
- Sugarcane residue, particularly bagasse, has the highest cost for sourcing biomass for cellulose dissolution.
- The sourcing of rice straw, among the most widely available residues, as bales is also among the cheapest options at 100 USD/tonne of cellulose.

Oil palm EFBs have the lowest total costs because their purchase costs are relatively low, since no competing uses exist. These residues can be bought at very low prices, have no storage requirement as their production is season-agnostic, and by nature are secondary residues that can be collected from oil extraction mills using larger lorries. Additionally, the large number of oil palm plantations contribute to a high availability of this residue. The opposite is the case for rice and

Figure 4.2: *Total average at-gate sourcing cost expressed in USD/tonne cellulose*



cereal straws, and sugarcane trash, as they need to be collected from every field, their transportation is challenging, and their seasonal nature requires storage facilities to ensure their availability throughout the year. These concerns can be addressed in part by combining rice straws with cereal straws that available in the remaining seasons of the year.

Another key conclusion that can be drawn is that densification through pelletization is very costly, and the lower transportation cost resulting from it does not compensate for the higher transport costs of the bales, as is evident from the comparison between the different chains in Figure 4.3 and Table 4.2.

For all delivery chains, the most dominant costs are the purchase costs. Transportation costs, even in cases of long distances and large bulk, is very small compared to the purchase costs. It is important to note that purchase costs are highly variable, and this analysis only uses rough estimates. Estimates were based on imperfect information derived from market prices that are hard to gather, and are affected by regional and temporal variations. Price levels are not published centrally or regularly, and an in-depth study would be required to determine a more accurate price that could be paid to farmers. Additionally, fixing the final purchase price requires an understanding of the essential farm-based costs to support the mobilisation of residual biomass for cellulose extraction for textile fibres. If prices remain too low, there is no incentive for farmers to supply agro-residues or make efforts to secure an additional income source.

Since transportation costs make up a relatively small share of the total delivery cost, the effect of distance is also limited. This becomes clear from Figures 4.4 and 4.5, in which the relationship between the distance to a hub location, the accumulated sourcing costs and accumulated cellulose, is displayed for selected hub locations. In West Bengal, the availability of rice straw is very large and spatially concentrated, and can support the sourcing requirements of a CD plant with a capacity of 500 kilotons/year within 20 kms assuming a 30% contractibility of rice straw in the region (Figure 4.4).

In case no purchase costs are considered, the average sourcing cost for straw bales is around 15 USD/tonne cellulose, and for pellets it is almost 80 USD/tonne cellulose. The transportation cost for pellets is limited and increases minimally with distance, while for bales these costs become steeper as distance to hub location increases (Figure 4.5). This is no surprise, since for EFB transport costs are the main cost item.

Figure 4.3: *Division of total sourcing costs into different cost items in USD/tonne cellulose*

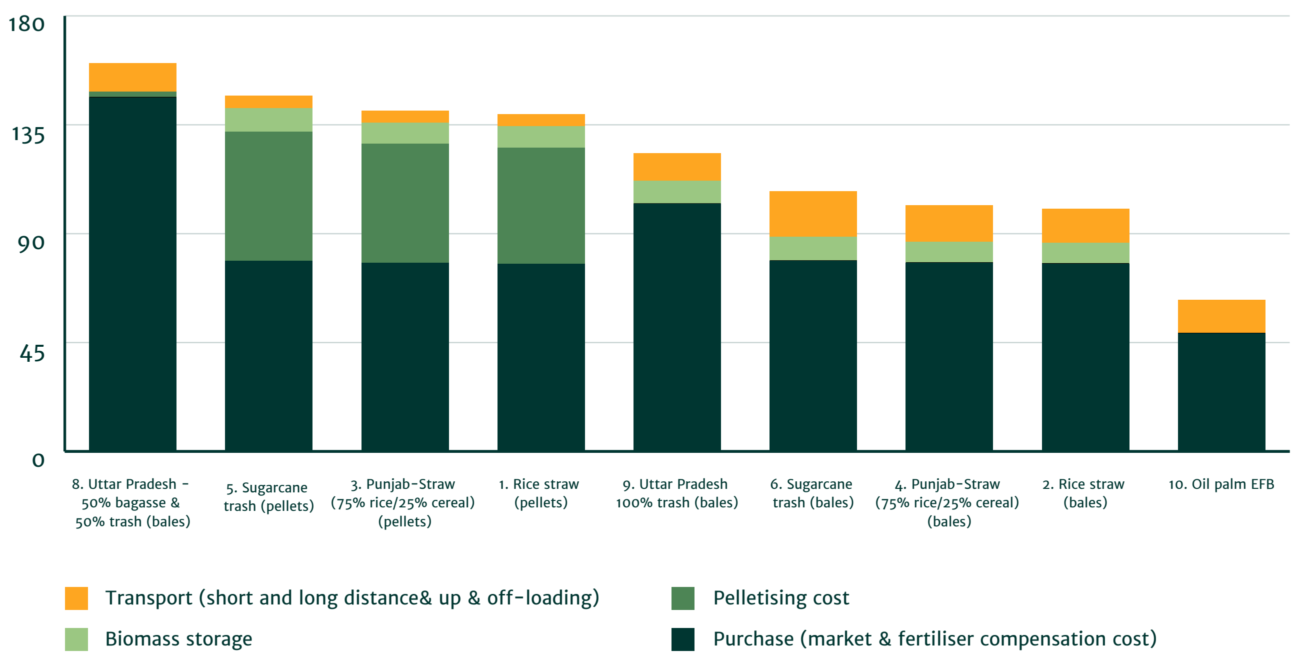


Table 4.2: *Cost calculation results at gate delivery of biomass for cellulose dissolving at plant gate*

		Hub	Plant sizes (Ktonne cellulose/year)	Total average cost (30% contractability) (USD/tonne cellulose)			Purchase cost (market & fertiliser compensation) (USD/tonne cellulose)			Pelletising cost (USD/tonne cellulose)			Biomass storage (USD/tonne cellulose)			Transport (short and long distance, and up- & off-loading) (USD/tonne cellulose)		
No.		no.		Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
1	Rice straw (pellets)	12	75/150/500	139	130	187	78	73	126	48	39	61	9	9	12	5	3	6
2	Rice straw (bales)	12	75/150/500	100	97	147	78	73	126	n.a.	n.a.	n.a.	9	9	12	14	10	18
3	Punjab- Straw (75% rice/25% cereal) (pellets)	1	150/500	141	–	–	78	–	–	49	–	–	9	–	–	5	–	–
4	Punjab - Straw (75% rice/25% cereal) (bales)	1	150/500	102	–	–	78	–	–	n.a.	n.a.	n.a.	9	–	–	15	–	–
5	Sugarcane trash (pellets)	4	75/150/500	147	143	167	79	70	103	53	52	55	10	9	10	5	4	6
6	Sugarcane trash (bales)	4	75/150/500	107	103	125	79	70	103	–	–	–	10	9	10	19	14	28
8	Uttar Pradesh – 50% bagasse & 50% trash (bales)	1	150/500	158	–	–	146	–	–	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	12	–	–
9	Uttar Pradesh – 100% trash (bales)	1	150/500	113	–	–	102	–	–	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	11	–	–
10	Oil palm EFB	1	75/150	63	–	–	49	–	–	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	14	–	–

Figure 4.4: *Cost distance relationship for pellets and bales from rice straw for hotspot in West Bengal in India*

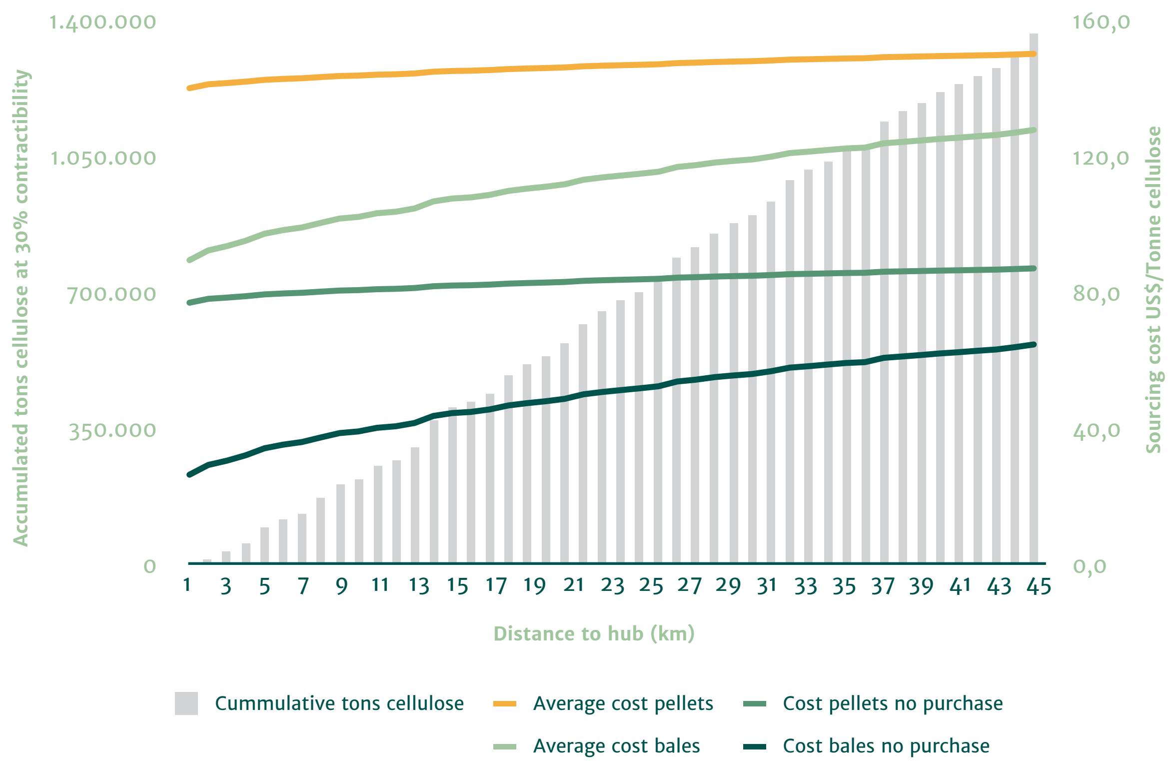
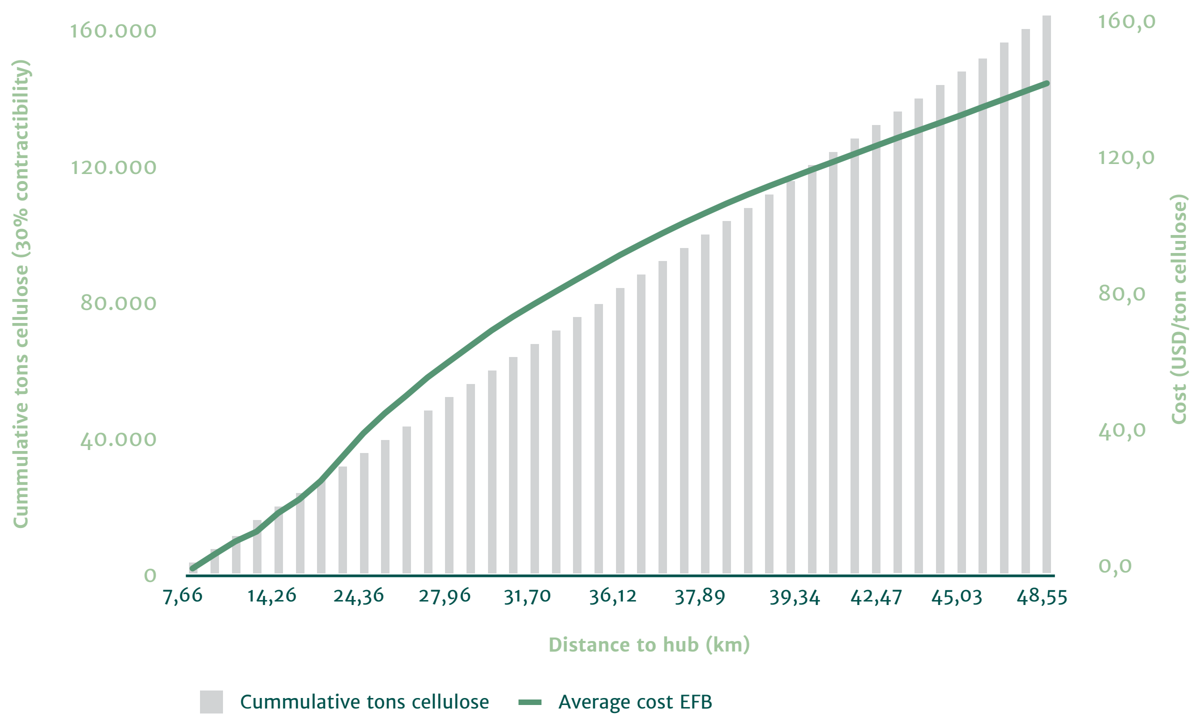


Figure 4.5: *Cost distance relationship for oil palm EFB sourcing to hotspot in Riau in Indonesia*



4.2.2 At-gate delivery costs for fibre rich biomass sources

The sourcing of the two residues selected for fibre extraction involves the transportation of very wet biomass – both banana pseudo-stem and pineapple leaves have more than 90% moisture content, when harvested.

An overview of the sourcing cost for these residues for the different hub locations is presented in Table 4.3.

Banana pseudo-stem biomass is delivered at lowest cost in Maharashtra, India and at highest cost in the hubs located in Vietnam and Thailand. This is due to a high concentration of banana plantations in Maharashtra that can provide biomass to

Table 4.3: *Overview of delivery cost of biomass to fibre extraction gate in USD/tonne of fibre for different chains*

S.No.	Country	Region	Sourcing feedstock	Average cost (USD/ tonne of fibre) 60% contractibility		Average cost (USD/ tonne of fibre) 30% contractibility	
				500 tonnes fibre/yr	1000 tonnes fibre/yr	500 tonnes fibre/yr	1000 tonnes fibre/yr
1	Bangla-desh	Khulna	Banana outer pseudo-stem	999	1,334	2,254	4,814
2	Bangla-desh	Khulna	Banana complete pseudo-stem	2,898	3,902	6,663	14,343
3	India	Maharashtra	Banana outer pseudo-stem	281	281	281	281
4	India	Maharashtra	Banana complete pseudo-stem	743	743	743	743
5	Thailand	Samut Pra-kan	Banana outer pseudo-stem	1,360	2,432	4,014	n.a.
6	Thailand	Samut Pra-kan	Banana complete pseudo-stem	3,979	7,195	11,943	n.a.
7	Vietnam	Kiên Giang	Banana outer pseudo-stem	1,560	2,689	4,334	n.a.
8	Vietnam	Kiên Giang	Banana complete pseudo-stem	4,579	7,968	12,903	n.a.
9	Indonesia	Jawa Barat	Banana outer pseudo-stem	885	1,362	2,201	3,481
10	Indonesia	Jawa Barat	Banana complete pseudo-stem	2,554	3,985	6,503	10,343
11	Thailand	Kamphaeng Phet	Pineapple	1,547	1,905	2,469	3,365

produce 500-1000 tonnes of fibre per year within a short distance and with minimal transportation costs (Figure 4.7).

For fibre sourcing residues, the cost structure is simpler than for cellulose-based biomass. It consists of three cost items: transportation cost, up- & off-loading cost, and purchase cost determined according to the fibre content in the residue. The latter is the reason that the purchase cost of pineapple is higher than that for banana pseudo-stems (Figure 4.6).

Two cases for sourcing banana pseudo-stems

For the sourcing of the banana pseudo-stem, two delivery scenarios are assessed. The first involves separation of the outer part of the pseudo-stem, which contains the fibres, and the rest of the biomass on the field. This is a labour-intensive process, but greatly reduces the amount of biomass to be removed from the field and transported. Using this measure, transportation weight is reduced to 30% of the original pseudo-stem volume in the field, but still retains a high moisture content of 90%. The outer pseudo-stem residues are collected at roadside and then transported to the fibre extraction mill. This lowers the transportation cost significantly. The purchase cost is higher for the outer pseudo-stem since it has about three times more fibre concentration than in the whole pseudo-stem.

The second scenario involves harvesting the whole pseudo-stem in the field and taking it to the roadside, where it is uploaded into a simple truck or cart for transportation to the fibre extraction mill. The harvesting of the whole pseudo-stem up to the roadside is assumed to be less labour intensive than the first scenario, but the volume transported is bulkier. Transportation costs are therefore higher per tonne fibre and more residues are removed from the field, which would need to be transported back to the field after extraction of the fibres at the plant.

On comparing the cost levels for the two sourcing scenarios, the results for two of the five regions indicate that the sourcing of the outer pseudo-stem is cheaper. The purchase costs are higher but fully compensated for by lower transportation costs. This is also shown in Figure 4.6, where cutting out the outer pseudo-stem reduces the sourcing cost significantly. Table 4.3 also shows that the overall sourcing cost of banana residues for fibre extraction is almost in line with the sourcing cost of pineapple leaves in most regions.

Additionally, spatial concentration and degree of contractibility strongly influence price levels, as illustrated by comparing the sourcing cost-distance relationship in Maharashtra, India and Samut Prakan, Thailand (Figures 4.7 and 4.8). The sourcing costs are significantly higher when the whole pseudo-stem is sourced in Samut Prakan. For 500 tonnes fibre, a price of 3000 USD/tonnes fibre needs to be paid, while in Maharashtra the price is not even 1000 USD/tonnes assuming the whole pseudo-stem is sourced. For outer pseudo-stem sourcing, this cost level is significantly lower, particularly in Maharashtra.

Figure 4.6: *Cost structure for sourcing outer and whole banana pseudo-stem in Khulna (Bangladesh)*

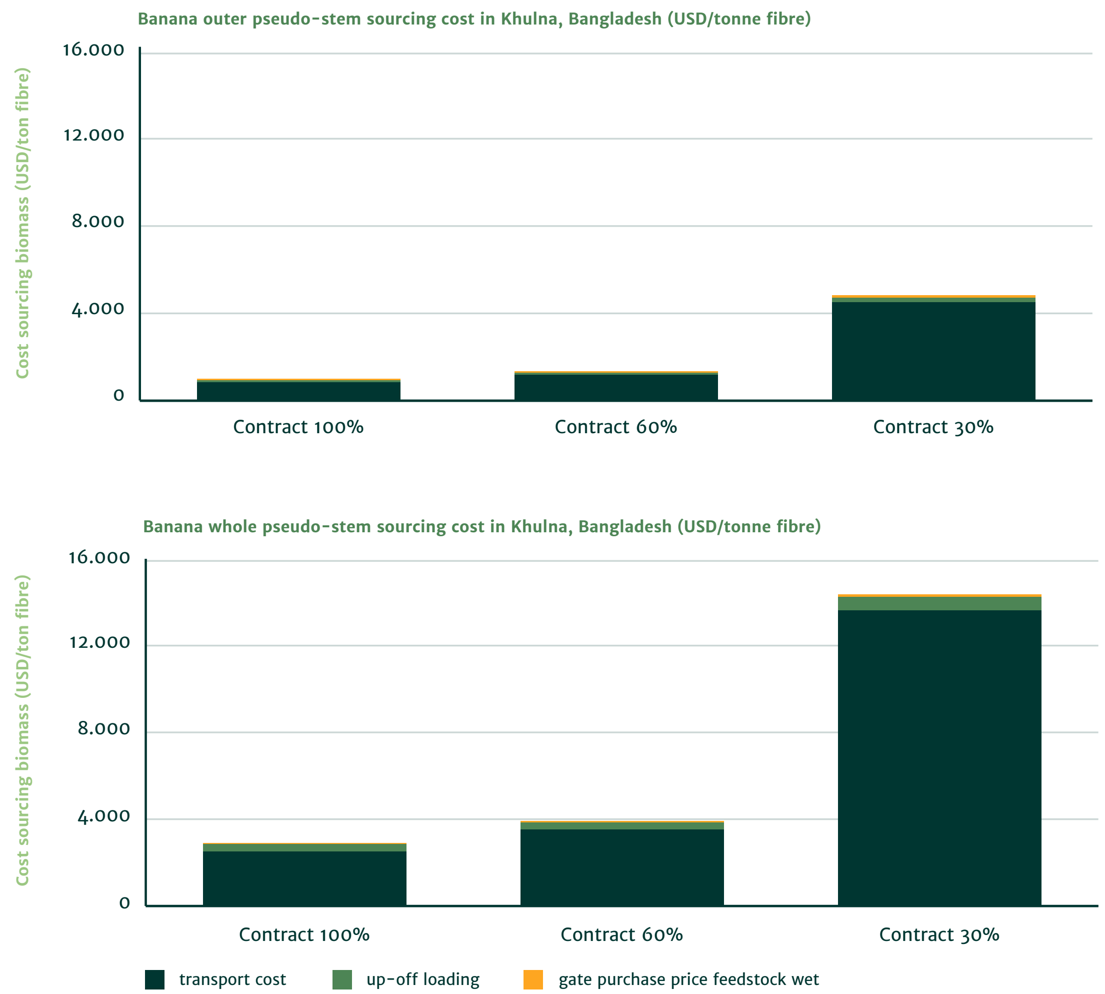


Figure 4.7: *Comparison between delivery costs of outer and whole banana pseudo-stems, and distance to fibre extraction plant in Maharashtra, India*

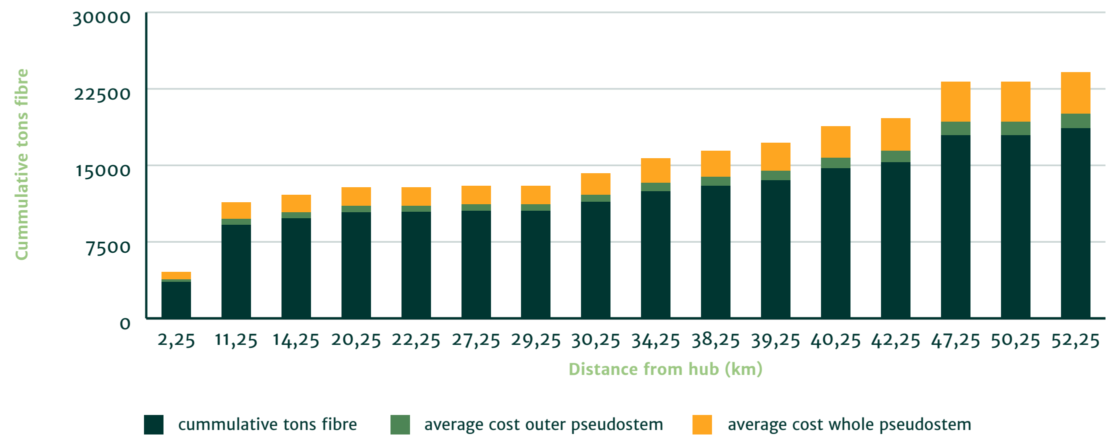
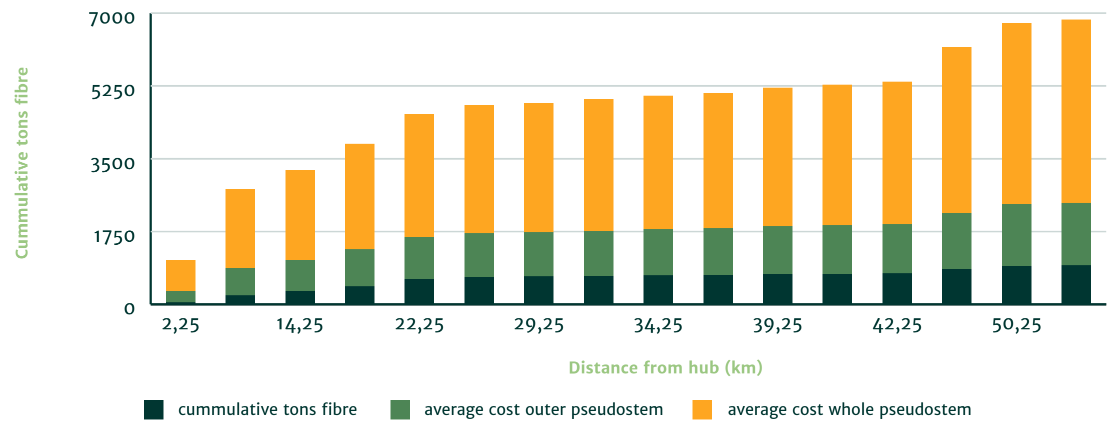


Figure 4.8: *Comparison between delivery cost of outer and whole banana pseudo-stems, and distance to fibre extraction plant in Samut Prakan, Thailand*



5

Landscape: Barriers, Opportunities and Sustainability

5 Landscape: Barriers, Opportunities and Sustainability

Previous sections assessed the physical availability of agricultural residues and their suitability as feedstock for textile fibres. Their potential to serve as viable commercial alternatives to conventional fibre sources is also dependent on structural factors relating to the landscape where these agro-residues exist i.e., the enabling environment, or surrounding ecosystem, including processing and manufacturing capacity, agricultural practices, transportation infrastructure, social and environmental priorities, among others.

This section considers and evaluates, from a theoretical perspective, the current value chain landscape across the following five dimensions:

- Agricultural production and practices
- Technology, design and innovation
- Processing and manufacturing
- Commercialization and scale up
- Socio-economic and sustainability perspectives

The information for this assessment was collected through consultations with stakeholders, sector experts and practitioners either working directly in these domains, or performing an ancillary function. These stakeholders offered pan-regional expertise, experience and insights that grounded the study's analyses, estimates and conclusions in real-world contexts (see Annexure 6). They illuminated prevailing trends and sectoral nuances that could influence and shape outcomes resulting from this study. A detailed description of these trends, including any opportunities or challenges they present, is provided in the following sections.

5.1 Agricultural production and practices

Seasonality – ensuring steady supplies of seasonally produced products

Agricultural production databases and numerical estimates show large potential agro-residue availability in the eight countries selected for this assessment. However, much like all agricultural products, their availability is seasonal in nature. For most crops, like rice, wheat and sugarcane, their highest volume is available during their annual growing season (planting to harvest). Out of season, their availability depends on their preservation and storage in safe facilities. Agro-residues follow these same trends. Due to textile manufacturing being a year-round industrial process, it becomes necessary to account for seasonal variability in the availability of agro-residue feedstocks, and consider options like pre-processing, densification and safe storage to ensure consistent supplies that align with demand.

Standardising quality across suppliers

Agricultural crops and yields differ across regions as a result of geographic and environmental factors like weather conditions, temperature, soil composition, and water quality, and also depending on the use of additives such as pesticides, fertilizers and other chemicals. Dominant consumer preferences may also affect the variety and quality of crops cultivated in a given region. Differences may also arise even between different farmers cultivating the same crop within the same geographic region. As a result, ensuring that agro-residue feedstocks consistently meet necessary standards regarding fibre length, uniformity and durability, can present a challenge.

Crop variability can be managed if manufacturers, individually or as a group, are able to specify required characteristics (type and quantity, quality, etc.) for agro-residues and communicate these to farmers and farm associations effectively – enabling growers to identify and deploy best-practice processes for delivering products to these standards. Such processes could include proper techniques for separation and removal from the field, pre-treatment processes that increase quality or durability, and safe storage methods that safeguard against spoilage, fire or other types of damage. Such processes could be tailored to the specific technologies or techniques used to extract cellulose from a given agro-residue.

The prevalence of decentralised, small-scale landholding patterns

Agricultural production in South and Southeast Asia, especially in the selected countries, is distinctive for its decentralised, even fragmented nature. Even in areas with relatively higher concentrations of a particular crop, small landholdings are the rule, with a high incidence of subsistence farming. Farmer associations are generally far and few, and middlemen or intermediaries dominate the stages between harvesting and sale of produce. This distributed, decentralised model poses challenges for sourcing agro-residues in commercially viable quantities for use by textile processors and manufacturers. Consolidating smallholder farms is not recommended, because it could lead to unintended or adverse social and financial repercussions. Alternative methods for aggregating agro-residues should be explored, including the establishment of farmer collectives and associations, which have proven effective and profitable in a variety of contexts.

However, it must be noted that aggregation and transportation costs of the agro-residues can become additional expenses. One of the possible ways of mitigating these costs is to explore options of breaking down the existing textile innovations into smaller processes that can be spread along the value chain. After the initial set-up costs, this can bring down the long run total costs and also help in greater community acceptance of these value chains (covered below).

Competing uses

Many agricultural systems and practices followed in South and Southeast Asia follow a regenerative or circular model of production. This ensures that the most parts of a crop plant such as husk, bran, stalks, stover, straw and skins are used as fuel, cattle fodder, fertilizer, or industrial raw material. The potential uses of agro-residues are broadly classified by the "Five F's" – fodder, fertilizer, fibre, feedstock and fuel. For example, in case of rice, rice husk briquettes are used to manufacture bricks. Rice husk can also serve as fuel to produce fly ash, which is used by the steel industry as a carbon source. Rice straw can be used as animal bedding, as compost, and to produce biogas (Koopmans and Koppejan 1997). Bio-fuels are a key competing use for residues from crops like rice, wheat, sugarcane and maize, which are increasingly used to produce biogas and bio-ethanol as alternatives to conventional fossil fuels (Box 5.1).

As agro-residues offer existing or potential alternative competing uses, these uses must be taken into account in assessing the feasibility and long-term

Box 5.1: Bio-fuel applications for agro-residues

Biofuels offer potential solutions to several growing global concerns including fluctuating oil prices, environmental threats, climate change, energy security and inadequate energy access in developing countries. In 2018, an estimated 160 billion litres of biofuels were produced globally (World Bioenergy Association 2020). After Europe and the Americas, Asia is the strongest player in the biofuels and bioenergy market. South and Southeast Asia particularly have seen a growing bio-economy in the last ten years. Examples include:

- In India, 34% of the annual gross crop residues is estimated to be a viable surplus for bioenergy production that could fulfill ~17% of the country's primary energy consumption. MNRE estimates about 2665 megawatts (MW) of power is generated by 288 biomass power and cogeneration projects and the surplus residue potential is the highest in Uttar Pradesh (40 tonnes), followed by Maharashtra (31 tonnes) and Punjab (28 tonnes) (Hiloidhari et al. 2014).
- In Thailand, sugarcane waste like bagasses and molasses are increasingly being used as a source for biogas and bio-ethanol. Since 2004, bio-ethanol from sugarcane grew to account for 59% of Thailand's total ethanol production (Gheewala et al. 2019).
- In Bangladesh, over 60% of total energy demand for cooking and heating, especially in rural areas, is met by biomass resources.
- The Vietnamese government has strongly promoted the use of bio-ethanol in place of fossil fuels. Currently, sugarcane molasses and cassava are used to produce bio-ethanol; but rice straw, which comprises 75% of agricultural residues produced there, is also being considered as a potential feedstock for ethanol production (Diep et al. 2012).

As noted elsewhere in this report, a number of concerns have been raised about the social and environmental impacts – and real sustainability potential – of bio-fuel production at large scale. While their potential is attractive in some ways, their long-term viability as fuel sources has yet to be determined or realised.

commercial viability of activating any given agro-residue as a feedstock for textile fibre production.

5.2 Technology, design and innovation

Lead times for testing and commercialization can constrain innovation

Research and innovation follow an iterative development process which involves multiple rounds of testing, error identification, correction and re-testing. A common observation among stakeholders consulted for this review, was it usually takes two to three years before a new technology or process can move from the concept stage, to a pilot project. It then takes another two to three years before the innovation can break even and become viable in the market. In a rapidly evolving and high-volume industry such as textile and apparels, these lead times are not considered encouraging for economic viability by most large textile brands. Therefore, many textile and technology innovators aim to develop concepts that are considerably ahead of the larger industry curve, while also being a lucrative near-term option for investors – a ideal balance that can be challenging to achieve.

Adaptability of current technologies and innovations to process different agro-residues

At present, most of the textile innovators focus on working with specific agro-residues that are available under very specific conditions. While these have achieved economic feasibility, these innovations currently are yet to explore other potential cellulose-based biomass residues. This largely limits the utility and scalability of their process/technology. Additionally, this assessment also found that these innovators have limited cross-sectoral interactions and operate independently of each other, in silos. This can adversely impact their versatility and adaptability to changing conditions in the market, in the long run. This barrier can be addressed if innovators explore the feasibility of processing multiple agro-residue types and sourcing locations. However, as majority of these are early-stage innovators, the level of risk involved may be cost-prohibitive.

Addressing the technical viability of agro-residue-based fibres for textile production – blending

Textile brands, manufacturers and processors note that in their basic composition and characteristics, agro-residue-based fibres currently don't offer characteristics that make them attractive replacement options for existing fibres. Critical requirements for softness, stretchability and flexibility are not completely met. Blending fibres becomes necessary step to address this challenge. Most textile innovators and manufacturers noted that blending is feasible with a conventional fibre, like cotton, in ratios such as 70:30 or 85:15, so that the conventional fibre acts like a carrier fibre. This allows the resulting blended fibre or yarn to retain most of the favourable properties of the carrier fibre, like strength and stretchability, while reducing cultivation needs by incorporating the agro-residue-based fibre. A target focus for future innovation, could be identifying favourable blends that improve durability, flexibility and elasticity while increasing the ratio of agro-residue-based to conventional fibres.

Retro-fitting existing technologies and processes

In general, it will be cheaper and easier to scale agro-residue-based fibre innovations if it involves minimal retrofitting of existing equipment and processes designed for conventional fibres – as opposed to establishing entirely new manufacturing models, which would be far costlier. Additional, in-depth cost modelling is recommended to identify optimal adaptation strategies for migrating production to a model that accommodates cellulose extraction and agro-residue-based textile manufacturing.

5.3 Processing and manufacturing

Pre-processing and shipping of agro-residue feedstock from source countries

Currently, textile production using conventional fibre sources is often concentrated in the Global South, where climatic conditions are conducive to diverse, year-round cultivation and labour costs are comparatively low. Yet many agro-residue innovators base their pilots – sourcing, extraction and manufacturing alike – in the Global North, nearer the headquarters of major textile brands. Full-scale commercialization may require transferring these innovations and related processing to source countries, and accounting for any resulting shipping, transportation and logistical costs as well as the resulting carbon footprint.

Regulatory and policy considerations

The agricultural sector is large and vital in all eight focus countries, representing a significant source of livelihoods, raw materials, nutrition and often, national pride. Unsurprisingly, agriculture – agro-residues included – garners significant attention and care in government policies and regulatory frameworks. These countries vary in their consideration of agro-residues, but often seek to promote organic and regenerative agricultural practices that support, for example, the use of agro-residues to produce compost to enhance soil health. As noted above, bio-fuels are also a focus in policies regulating agro-residues. Comparatively, the use of agro-residues in textile fibre production is a new proposition, as yet almost unconsidered or unaddressed in most existing policy frameworks.

Cluster-based aggregation and processing – a promising model

As noted earlier, the fragmented geographic distribution of agriculture with small landholding patterns in the eight focus countries, poses a challenge to the generation and collection of adequate quanitites of agro-residues for textile manufacturing. Some innovators-cum-manufacturers have already devised aggregation mechanisms that partially address this challenge. The most commonly followed aggregation technique involves breaking down the processing into different stages, and setting up localised aggregation centres with small-scale processing mills within a defined radius of a cluster of farms. These aggregation/processing clusters cover the collection and pre-processing of agro-residues from farms located within a radius of 20-50 kms. The processed outputs from these clusters are then transported to a larger processing plant, which serves as a central hub for several such smaller clusters. Such a model allows manufacturers to limit the costs involved in long-distance, cross-regional shipping, while also investing in the local economy around each sourcing location. Storage infrastructure is also a key component in such a model.

Heavy dependency on locally available infrastructure and resources

Countries in the Global South are marked by their relatively lower levels of industrialization, technological advancement and limited infrastructural development, as compared to those in the Global North. While the eight selected countries in this study continue to develop and expand their economies, existing infrastructure around the selected agricultural belts in these countries including roadways, end-to-end connectivity, mobility options, and availability of energy and water, may not be adequate in every community to support the logistics of local value chains to transport and process agro-residues for textile production. Significant initial investments and capital could be required to establish such value chains and ensure their continued maintenance and repair. Most private entities will find such expenses beyond their scope, and will need to rely on partnerships with the local government and authorities, and/or with other local players like textile manufacturers/brands, farmer associations, and transportation services.

5.4 Commercialisation and scale-up

Long-term contracting to ensure year-round supply

High seasonal dependency of agro-residues leads to uncertainty in ensuring a stable supply of feedstock over time. Consultation with a leading textile innovator-cum-manufacturer revealed one way to circumvent this challenge – long-term contracts with farmers in the sourcing countries, to ensure a guaranteed agro-residue quantity in accordance to a set of pre-defined quality parameters outlined by the manufacturer.

These contracts can be made lucrative by incorporating incentives for meeting the stated agro-residue supply and quality requirements, such as time-based incremental unit pricing. These incentive-based contracting arrangements offer supply stability to manufacturers, enabling them to plan for longer horizons and expand their operations. Additionally, local farming communities gain access to a viable economic growth path.

Box 5.2: Long-term supply contracting with pineapple cultivators

Long-term supply contracts are particularly useful when there is limited availability of residues that require certain pre-defined quality standards to be met. A leading European textile innovator and manufacturer working with pineapple residues has developed a model in which the sourcing of residues, along with pre-treatment processes, are carried out in a tropical country in Southeast Asia. Due to the specific residue demand and geographic availability of the pineapple residues, the textile manufacturer opted to enter into long-term contracts with the local agrarian communities involved in pineapple cultivation.

These contracts have helped ensure a steady supply of pineapple residue feedstock over time for production, while also incentivising the farmers by factoring in the market conditions and prevailing trends at regular intervals to determine the final prices they receive. Additionally, the innovator regularly conducts training workshops for these farmers to improve their cultivation practices and ensure removal of pineapple residues using proper techniques. Such contracts demonstrate that a long-term relationship between innovators and local farming communities, can provide an alternative and steady source of income to farmers while securing long-term supply stability for the innovator – resulting in a self-sustaining, cross-sector local stakeholder network.

Pricing implications for the final product

A number of factors are expected to influence the price of the final textile produced from agro-residues. The shared perspective among the consulted textile manufacturers, innovators and large retail brands is that the manufacturing costs associated with setting up new value chains that would support the aggregation, processing, storing and shipping of agro-residues, are expected to be at a premium. Additionally, the costs of installing and running innovations and technologies required to process agro-residues would be higher.

Thus, the collective outlook is that at least initially, the price of a final textile product made from agro-residues would be higher than prevailing market prices for its competitor products. Optimization of costs and prices, along with tapping into a large consumer base, is expected to happen over a longer time horizon.

5.5 Socio-economic and sustainability perspectives

Community engagement and developing local economies

Agrarian communities play a pivotal role in building a textile value chain based on agro-residues. Farmer buy-in is an essential component to ensuring adequate supply, proper harvesting, and consistent quality for ultimate textile processing and manufacturing. It is critical for textile manufacturers, particularly those who intend to source directly from farmers, to engage closely with and form mutually beneficial partnerships within local agrarian communities. Livelihood diversification, incentive programs, and local capacity building programs are some ways manufacturers can engage productively with communities and boost local economic development around agro-residue sourcing hubs.

Sustainability assessment and certification of new textile value chains

An increasing number of textile brands and manufacturers are seeking alignment with globally recognized certifications and standards to benchmark their value chain sustainability, minimise environmental impact and improve consumer perception. GOTS (Global Organic Textile Standard), bluesign, ZDHC (Zero Discharge of Harmful Chemicals), ECO PASSPORT by OEKO-TEX and Responsible Care are some well-known textile sustainability standards. While agro-residue-based value chains offer a potential pathway to establish low-impact, environmentally conscious production and boost social value, it will be important to ensure that these comply with the existing sustainability standards, specifically those for bio-based value chains (see Box 5.3).

Possible unintended and environmental consequences

The unique value of bio-based value chains and production models stems from their potential to de-couple economic growth from fossil fuel dependency, and their higher degree of biodegradability. These benefits could obscure an understanding of the overall environmental impact and sustainability of these value chains. Potential unintended consequences that could accompany these value chains include changes in agricultural practices, depletion of soil nutrients, introduction of industry-focused agricultural systems, unsustainable demand for agro-residues, or dependency on additives or intensive farming practices to meet residue quality requirements. These effects could be exacerbated as these textile value chains find commercial viability and move towards increasing scales of production.

As a prescriptive counter-measure, the commoditisation of agro-residues can be accompanied by the development of agro-residue focused policies that standardise sustainable utilisation, and define stakeholder responsibilities for ensuring effective implementation. Local NGOs working in natural resource management could serve as important non-partisan members in these stakeholder networks, and help balance commercial pursuits with strong representation for local agrarian communities. In the short run, a life cycle assessment of the proposed value chains is recommended to assess its true value as a sustainable and environmentally conscious model.

The next section delves in more detail into the potential climate change and environmental considerations, in particular, that can accompany these value chains.

Box 5.3: Assessing and certifying the sustainability of agro-residue based value chains

The Roundtable on Sustainable Biomaterials (RSB) is a leading global certification body that conducts sustainability assessments for value chains and products using bio-based feedstocks and materials, including biomass and biofuels. Using a set of 12 sustainability principles, RSB assesses the potential environmental, economic and social impacts surrounding bio-based and recycled carbon products and fuels, at every stage of the value chain –producer, processor, supplier, and end-user. It follows a risk-based approach to identify and prioritise specific risks for a given regional and contextual scenario.

For agricultural residues, RSB standards cover bio-based feedstocks and advanced products that utilise residues from crops like sugarcane, wheat, maize, sorghum and oil palm. It also outlines sustainability standards for novel and established technologies and processing techniques that utilise biomass or recycled carbon feedstocks. Some of the key assessment criteria include sustainable removal, soil conservation, protection of forests, local livelihoods, food security and GHG emissions, to ensure overall environmental and social sustainability for a growing global bio-based and circular economy.

RSB's certification process and standards are acknowledged as rigorous, reliable and user-friendly by sustainability leaders like UNEP, WWF, IUCN, NRDC, Blue Angel and Canopy. The European Union and Japan, among others, recognise and provide preferential market access to RSB-certified materials.

5.6 Climate change and environmental externalities

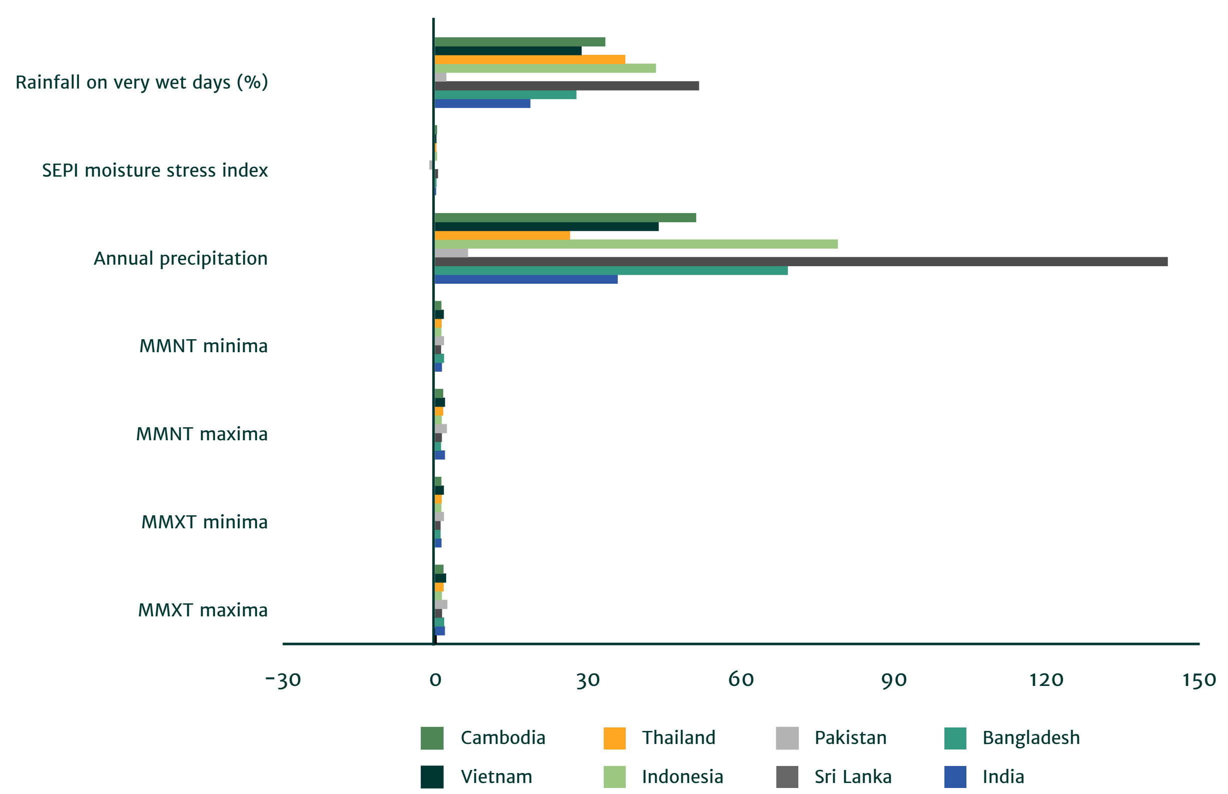
South Asia and climate change

Countries in South and Southeast Asia are largely rural agrarian societies. A majority of the workforce in these countries (~40%-60%) derives its livelihood from the agriculture sector. Yet agriculture in these regions is largely rainfed, dependent on the south-east or north-east monsoons (barring the tropical climate of islands in Indonesia), with most of these countries facing high vulnerability to climate change and related disasters and extreme events like droughts, floods etc. Seven out of the eight countries being assessed, are among the top 20 most vulnerable countries to climate change, based on the Global Climate Risk Index 2019 (David Eckstein and Winges 2018). Temperature projections for the eight countries estimate a rise in Mean Maximum Temperature (MMXT) and Mean Minimum Temperature (MMNT) of 0.87 to 2.22° C by 2040-59, while annual precipitation is projected to increase by 6.21mm to 143.61 mm[11].

Climate and environmental impacts on agriculture

Climate variables like temperature, rainfall, soil moisture and carbon dioxide concentration are critical for agricultural productivity and have different, non-linear impact on different crops. For example, the IPCC AR4 suggests an increase in the yield of C3 crops (rice, wheat, banana, coconut and cotton) by 10-25% and increase by 0-10% for C4 crops (maize, sugarcane and pineapple) when atmospheric CO^2 levels reach 550ppm due to carbon fertilisation (Zhai and Zhuang 2009). However, there are also studies indicating that climate variability and associated changes can potentially reduce agricultural production by 5-20%, particularly in countries like Indonesia where the number is as high as reducing rice yields by 20% and maize yields by 40% (Ananda and Wododo 2019). Climate change has also increased the incidence and threat of disasters and extreme events. Intensive land-use and unsuitable production practices often contribute to increasing the vulnerability of crops to disasters, and farmers have limited capacity to cope with them. Some of the major impacts are given below:

Figure 5.1: *Changes in climate variables for 2040-59*



Note: All projections for 2040-59 based on RCP 4.5 emissions and Ensemble model.

Soil health and conservation: Soil health is a key determinant of crop productivity. Climate change accentuates the existing vulnerabilities related to land degradation while adding new challenges. The climate projections in Figure 4.12 indicate the increased stress in soil moisture. There is also an increased threat of soil salinisation due to higher evaporation rates associated with higher temperatures, and due to sea level rise in coastal areas that causes salinity intrusion in lower delta regions. This is of particular concern in the eight countries studied as they have extensive agricultural land in downstream regions. Further, soils are a rich ecosystem that serve as important carbon sinks. If inappropriately managed apart from a reduction in the productivity of crops, soils can turn into another source of carbon emissions (European Environment Agency 2020).

Diseases and pest attacks: Higher temperatures and low moisture can increase abiotic stress on plants, increasing their susceptibility to attacks from pathogens (Cohen and Leach 2020). This is a major concern for developing countries, where agriculture is increasingly shifting towards monoculture, particularly for fruits like banana, and oil palm in Indonesia (Fones 2020). Indonesia is a classic example, where preference for cash crop cultivation has meant that hundreds of acres of forest land and biodiversity are routinely being cleared to make way for palm oil. Monoculture often contributes to soil degradation and other detrimental environmental consequences, as well as reduced ability to withstand pests. The 2020 locust swarm attack in South Asia is an indicator of the new pest attacks to which these countries might be exposed.

Effect of crop residue burning: Besides climate change, environmental repercussions also accompany different cultivation and harvesting patterns. For example, residue burning contributes to increasing the concentration of aerosol particles like PM_{10} and $PM_{2.5}$ in the air, a recurring trend in North India during the months of October and November. Rice straw has limited use apart from cattle fodder, and a majority of farmers (S. Kaur 2020) cannot afford more expensive straw management machines like the 'Happy Seeder'. A recent study found that an estimated 20.3 Mt and 9.6 Mt of crop residue was burnt in Punjab and Haryana, respectively (Singh et al. 2020), for the agricultural year 2017-18, resulting in an emission of 137.2, 56.9 gigagrams of $PM_{2.5}$ and 163.7, 72.1 gigagrams of PM_{10} respectively for the two states. Rice and wheat are the major contributors to burnt residue (>90%), leading to high-quantity atmospheric emissions in the Indo-Gangetic plains. Similar trends in residue burning practises have also been observed in Cambodia, Indonesia and Thailand (Kumara, et al. 2020) (Vibol and Towprayoon 2009).

Dominant practices: Agriculture in South and Southeast Asia is also characterised by intensive pesticide use and groundwater extraction – environmental consequences that are often misaddressed by policy regulations and incentives. The incorrect disposal of pesticide wastes contributes to the pollution of groundwater, surface water, and soil – for example, pesticide residues have found to be 33% above maximum residue allowances in samples from Vietnam, and 9% in Thailand (Skretteberg et al. 2015). Thus, when considering the potential of crop residues for textile production, it is important to understand the prevalent cultivation practices in the major producing regions, so as to map their environmental footprints and discourage prevailing unsustainable methods, along with building resilient agricultural systems to withstand climate stressors and ensure production at scale.

Regional trends in agriculture for climate change adaptation

While climate change poses disproportionate risks to farmers and communities in the eight countries, the countries are increasingly aware of these. All the countries have adopted their own approaches to improving adaptation and resilience to climate change, particularly in the agriculture sector. Broadly, the major trends and approaches observed are (see also Annexure 8):

11 These projections are as under RCP 4.5 (Representative Concentration Pathway), or the intermediate scenario where emissions peak by 2040 and then decline, as per the Intergovernmental Panel on Climate Change (IPCC). The model used is an Ensemble model.

- **Projected increases in temperature and precipitation are largely expected to decline agricultural yields** of most of the selected crops across the major production belts in the focus countries, in both low- and high-emission scenarios.
- **However, there are some non-linear trends.** In some instances, like banana – in 27 countries accounting for 86% of global dessert banana production, changing climate conditions since 1961 has increased annual yields. However, these could dampen to 0.59t/Ha and 0.19t/Ha by 2050 under the climate scenarios for RCP 4.5 & 8.5 respectively, driven by declining yields in the largest producers (Varma and Bebber 2019). Another example is maize cultivation in Indonesia, where areas with increased rainfall will see a positive effect on yields, while those with higher temperatures will experience reduced yields, the net result being positive (Hecht 2016).
- **In addition to droughts brought by increased temperatures, sea level rise and saltwater intrusion leading to high salinity is another threat posed by climate change.** Studies indicate the high threat of salinity to crops like rice, okra etc. across coastal and low- lying regions in countries. For example, sea level rise and saltwater intrusion could reduce rice yield by 15.6% in nine coastal sub-districts (Dasgupta, et al. 2017).
- **Cultivation practices like intensive pesticide use, can also contribute to negative consequences.** For example, the carbon footprint of pineapple cultivation in Thailand for 158 ha. area was found to be 172 g CO2eq/kg of fresh pineapple with main contribution from fertilizer usage (Usubharatana and Phungrassami 2017).
- **Countries are devising different strategies to adapt to the vagaries of climate change – a combination of changing both farming practices, and market mechanisms.** These include shifting to hybrid and nitrogen-efficient crop varieties, production technologies with lower demand of water and fertilizers, crop diversification, and practices like double mulching, System of Rice Intensification (SRI) etc. There are also efforts to shift away from malpractices and have more effective disease and pest control measures.

Efforts to reduce agriculture-related GHG emissions or investments for mitigation in the agriculture sector, still remain on the lower side. Apart from a handful of implicit domestic projects (like in India) and a few internationally funded efforts (World Bank in Sri Lanka and Bangladesh, and ICRISAT in India), Climate Smart Agriculture (CSA) projects aren't as popular (Kishore, et al. 2018, World Bank 2020, World Bank 2019, ICRISAT 2016). The adoption rate of CSA practices is also low in these countries. (CIAT; World Bank 2017, CIAT; World Bank 2017, Ninh, et al. 2017, World Bank; CIAT 2015). Further, there are instances when short-term livelihood interests overshadow the long-term sustainability and ecological interests in the local context. In the absence of appropriate political will, as well as incentives for local communities and monitoring of progress, these agricultural lands and communities face even higher risks.

Effects of regional differences and temporal variability in climate change – A caution

While this section highlights the major findings published in the public domain for identified crop-country combinations, there are limitations on the extent to which they can be relied on for activities envisaged under this assessment. There are wide regional variations in productivity and climate vulnerabilities, which may differ from those projected at the national level, and extrapolations do not accurately represent ground-level realities or inter-regional variability. There are also significant variations of climate impacts based on a crop's genetic variety.

For certain crops, there is inadequate research on country-specific impacts of climate change, like okra in Pakistan, and coconut and pineapple in Indonesia. Further, data collection and representation regarding crop yields is not uniform across countries and thus, cross-country comparisons may not be appropriate. For instance, Indonesia uses total harvested area for calculation of productivity (yield) while Bangladesh, India and others, adopt gross cropped area.

Due to limitations of time, the focus was on the medium-term climate scenario of 2040-59 and RCP 4.5 scenario alone to assess the relative vulnerabilities. The most prominent published literature on documenting climate vulnerabilities as well as other environmental externalities, and emerging new trends in farming practices was also reviewed. In terms of geography and farming practices, South Asia and Southeast Asia are very diverse. There is a need to dive deeper to identify specific climate vulnerabilities and potential impact on crops and residue, as well as on supply chains and technologies that can enhance the commercial viability of converting agro-residue to textiles. This would help avoid unintended negative environmental impacts, and build resilient systems that can endure climate shocks.

Policy-data interplay, guiding environmentally conscious decisions

Development imperatives often drive key stakeholders in the agriculture sector to make decisions on how to use land and where to invest resources. For example, switching to cash crops and monoculture often leads to negative environmental consequences in the long run. The negative impacts are further exacerbated by climate-induced changes. The textile and fashion industry too, plays its part in adding to these negative consequences. Using agricultural waste and feedstock in an environmentally conscious manner is a welcome step to making the fashion industry more responsible, and sustainable. Sustainability of feedstock depends largely on the health of the ecosystem, namely water, soil and biodiversity. While focusing on the possibilities to offset farm-level consequences, rigorous efforts are needed to contain the off-farm challenges mainly arising out of skewed economic, social and environmental policies.

Today, there is a wide choice of advanced technologies and dissemination tools to inform stakeholders to measure, monitor and take appropriate actions. It is important to build off existing knowledge and develop a risk matrix for cultivation systems for the selected crops in this assessment study. This can incorporate provisions to understand both the impact of climate and environmental risks, while identifying optimal methods of yields. This will be an important step to address the existing data and knowledge gaps and leverage the niches available to make the textile industry more sustainable and greener going forward.

6

Roadmap towards Commercialisation

6 Roadmap towards Commercialisation

This report documents a detailed and thorough evaluation of the availability, suitability and feasibility of agro-residues as a viable alternative feedstock for textile fibres supplying the global apparel and fashion industries. This section reviews key findings, summarizes opportunities and barriers for commercialising these alternative value chains at scale, and proposes next steps industry stakeholders and others can consider to accelerate activation and maturation.

6.1. Key findings – A review

Agro-residues represent a viable and potentially valuable lever for addressing integrated economic, social and environmental challenges in the textile supply chain. They offer the potential to: advance sustainable apparel; increase the uptake of regenerative agricultural practices in agricultural communities; and, create new and relatively resource-light revenue streams for low-income farmers in South and Southeast Asia, and likely, in many other agricultural regions globally.

As of today, the processes and systems that enable converting agro-residues to fibre are still in their infancy. A range of technological, logistical and commercial challenges will need to be overcome to achieve commercialisation at the scale required for agro-residue-based fibres to be established as a significant percentage of global fibre supply for the textile industry.

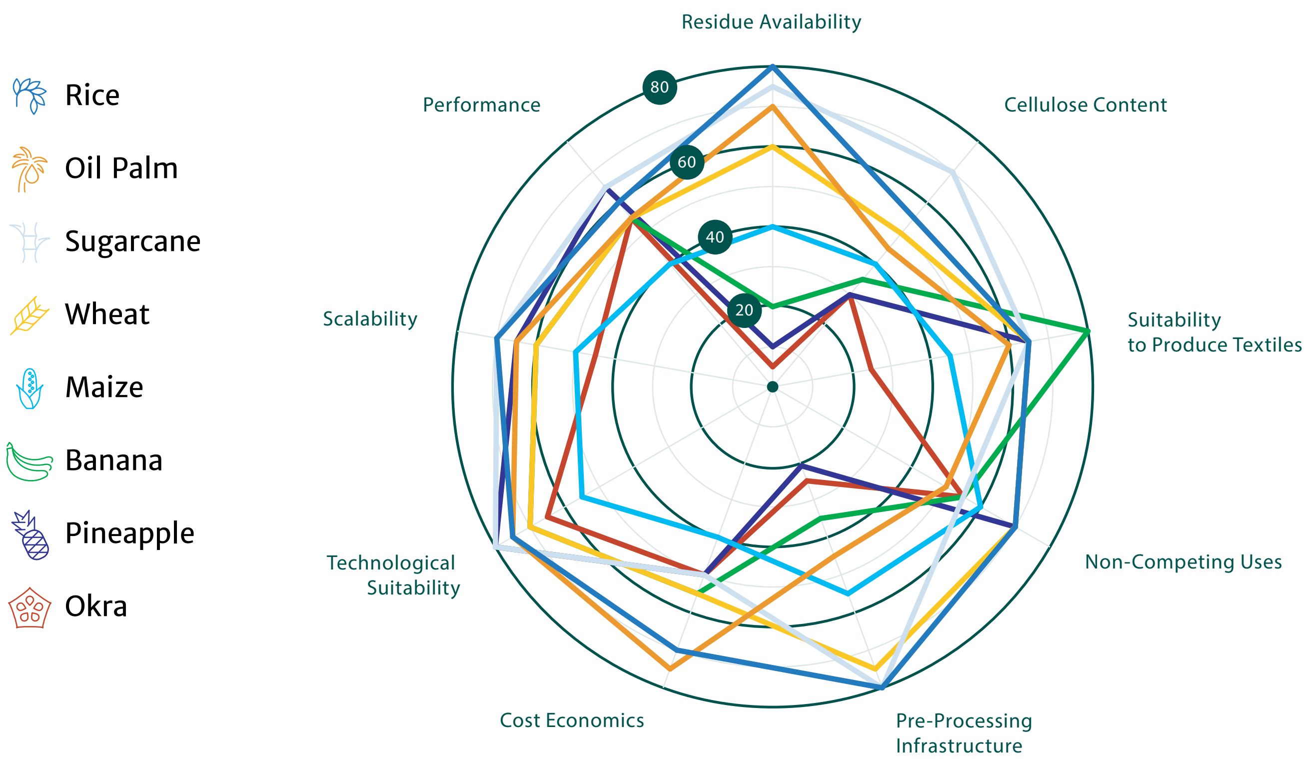
Agro-residues that offer optimal promise for commercialisation

This report assessed an exhaustive list of agricultural products and by-products across nine dimensions of suitability and feasibility for uptake as fibre feedstocks – availability, cellulose content, suitability to textile production, competing uses, cost considerations, existing technology, existing infrastructure, performance, and potential for scalability. Figure 6.1 shows raw scores, on a scale of 1 to 100, for eight different agro-residue crop sources across all nine dimensions.

Based on this assessment and subsequent analysis, the following conclusions can be drawn:

- Across all eight countries, rice and wheat straws/husks, and sugar bagasse, have the highest and most consistent widespread availability.
- EFBs from oil palm, while less widespread, join the top of the suitability list because they lack major existing alternative uses.
- Rice, wheat and sugarcane all offer existing, basic pre-processing infrastructure – other crops, like banana and pineapple, could require higher processing and set-up investments due to their comparatively high moisture content.
- Rice husk and oil palm offer the best cost economics. Bagasse, with its higher cellulose content and yield potential, also offers attractive cost parameters.
- Overall, the findings indicate that rice husk and rice straw offer the largest potential across all eight countries. Wheat straw, bagasse, banana plantain, maize and sorghum also offer potential if technical challenges to optimal cellulose extraction (like silica content) can be overcome.

Figure 6.1 *Priority matrix for the top combinations*



Important considerations and potential barriers for optimal configurations

The report identifies the following key considerations and potential barriers for activating, optimising and commercialising potential agro-residue/fibre feedstock systems:

- The costs and logistics of harvesting, collecting, densifying, storing and transporting agro-residues are critical factors. This is a systems challenge, involving collaboration among disparate stakeholders and dependant on local conditions and infrastructure.
- Purchase and transport costs are generally the highest cost hurdles in activating agro-residue chains for processing in bulk. These can be mitigated by identifying areas where agro-residues are available in large volumes, and are co-located with near-by processing capacity. The closer processing sites are to the residue source, the more stable supply logistics will be.
- Therefore, infrastructure is the biggest logistical challenge and cost variable – i.e., the extent to which farms and farm communities are in sync (geographically and systemically) with, have working relationships with, and are readily accessible to, transporters, processors, millers and manufacturers. Several of the recommendations in this report center on this challenge.
- A stable, sustainable agro-residue capture and processing operation is a cross-sector system involving effective collaboration among disparate stakeholders. Successful pilots to date have accounted for this through targeted, multistakeholder community engagements; tie-ups between larger farmers or farm collectives, and mill associations; and the use of third-party aggregators whose express purpose is managing relationships between various commercial partners.
- Soil health must be maintained, and any potential adverse effects mitigated. Soil quality is a critical component of sustainable agricultural production. Accommodation must be made for leaving nutrients on the field where possible, and/or, returning unusable product to the field after usable cellulose is extracted.
- Competing or alternative uses for agro-residues must be catalogued, mapped and accounted for. In some cases, agro-residues may be used for nutrient management (compost, manure), livestock feed, or alternative energy (bio-fuels). These uses and their impacts on local ecosystems, agricultural practices, and cost implications must be evaluated case by case.

6.2 Recommendations – A roadmap to tipping the scales toward sustainable fibre value chains

Following is a list of recommendations, organised across four key topics:

R1. Investing in additional targeted research or study
R2. Geographic and spatial considerations – where to focus, and why
R3. Decentralize and diversify – iterate to innovate
R4. Stakeholder engagement, industry leadership, and tools for acceleration

Figure 6.2 provides an overview of the stage-specific recommendations to build an overall ecosystem for the alternative textile value chains based on agro-residues.

R1. Investing in additional targeted research or study

Efforts to further activate and mature commercialised agro-residue value chains would benefit from additional research or study into:

- Benchmarking for purchase costs and price structures for a given agro-residue and geography, accounting for market factors and socio-economic/environmental factors.
- The actual availability yield of agro-residues in selected locations. Residual biomass potential is determined not just by physical availability, but ultimately, by what can actually be mobilised once collection, processing (e.g. for high moisture content, or densification), agronomy, environmental concerns, and transportation are accounted for.
- The nuanced social, environmental, climate and overall sustainability impacts of specific models at scale. Most data are only available from pilot-scale projects that can't account for the effects of large-scale implementation on factors like emissions, climate mitigation, social equity and rural livelihoods. Better modeling, statistical analysis, and participatory assessments are needed to develop more accurate evaluations of impacts and implications.

R2. Geographic and spatial considerations – where to focus, and why

- This study identified at least 10 hubs across South and Southeast Asia well positioned to become hubs for agro-residue-based fibre production, based on high biomass concentration, existing infrastructure, proximate processing capacity, and co-location with segments of the textile manufacturing supply chain. These include locations where plants producing 500,000 tonne or more of cellulose per year should be feasible from a sourcing perspective. These locations include:

  EFBs from oil palm:
  - Surat Thani, Thailand
  - Riau, Indonesia

  Straw from rice:
  - Sindh, Pakistan
  - Andhra Pradesh, India
  - Suphan Buri, Thailand
  - Takêv, Cambodia
  - Polonnaruwa, Sri Lanka
  - Jawa Timur, Indonesia

  Combination of rice straw with cereal straw:
  - Punjab, India
  - Rajshahi, Bangladesh
  - West Bengal, India
  - Thái Bình, Vietnam
  - An Giang, Vietnam
  - Jawa Tengah, Indonesia

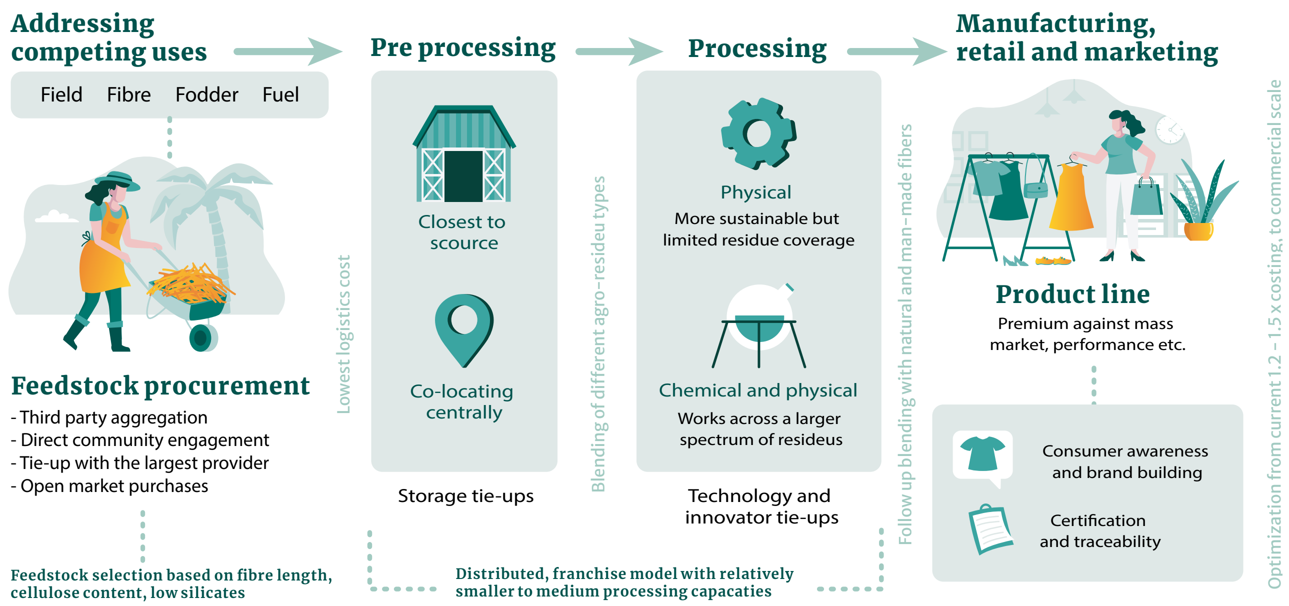
  Trash and bagasse from sugarcane:
  - Uttar Pradesh, India
  - Punjab, Pakistan
  - Maharashtra, India
  - Uthai Thani, Thailand
  - Lampung, Indonesia

  Banana pseudo-stems:
  - Maharashtra, India
  - Khulna, Bangladesh
  - Samut Prakan, Thailand
  - Kiên Giang, Vietnam
  - Jawa Barat, Indonesia

  Pineapple leaves:
  - Kamphaeng Phet, Thailand

- Cellulose extraction based on EFB from oil palm mills are possible in Indonesia and Thailand, but plants should remain modest in size. EFB's offer high cellulose yields and currently have limited or no competing alternative uses, but the authors recommend caution with this commodity, as its use could lead to an expansion in oil palm cultivation – a sector already challenged by documented and significant sustainability challenges.
- For this study, hub recommendations were made based on size and yield potential of available agro-residues, and proximity to industrial and urban locations. For final selection, the authors recommend integrating other factors including logistical infrastructure, interest of local actors, textile production flows, market stability, etc.

Figure 6.2 *Stage-specific recommendations to build an ecosystem for alternative textile value chains*



R3. Decentralise and diversify – iterate to innovate

- A strategy to innovate alternative agro-residue textile supply chains will benefit from a more distributed processing model than has been typical to date in apparel manufacturing.
  - Agro-residue processing is currently a highly local affair, best tailored to the unique agricultural, socioeconomic, industrial and logistical considerations of any given residue and geographic combination. On-ground partnerships between manufacturers and residue-providers offer the most promising potential.
  - Unlike wood and forest residues, which work well with physical processing only, agro-residues generally work best with a combination of physical and chemical processing. The environmental, social and economic implications of scaling any given residue are varied and unique, and have to be approached accordingly.
  - New technologies require several rounds of iterations, in the lab and in the field, in order to properly demonstrate mainstream pilot manufacturing potential.
- As a result – as well as the advisability of maximising proximity of agro-residue resources to processing capacity – in the near-term, iterating a set of distributed local efforts will likely prove more effective than investing in larger, individual vertical efforts.

R4. Stakeholder engagement, industry leadership, and tools for acceleration

A set of actions and steps have been identified that the apparel and fashion as a whole – and particularly, brands and sector leaders – can take to activate and accelerate the commercialisation of agro-residues as a sustainable alternative fibre feedstock:

- **Establish a South/Southeast Asia Fibre Alliance.** The industry should establish a steering and exploratory alliance to help drive coordinated and ambitious action across the region. The Alliance should include key academic and research institutions (ICRISAT, MSSRF), current innovators (Spinnova, Nanollose, Agraloop, Phool, etc.), leading brands, manufacturers and local industry associations (Ramatex, Arvind, Dyers Association of Tirupur, etc.), farmer cooperatives, and government extensions (Krishi Vikas Kendra's), and should include regional sub-platforms. The Alliance should aim to boost collaboration around targeted investments in infrastructure, technology, manufacturing tie-ups, and stakeholder engagement. The Alliance would bring together key players, spread risks and costs, help source and process agro-residues, ensure sustainability, and advance technological innovation.

- **Conduct intensive stakeholder community-based engagement and relationship building to strengthen the enabling environment for agro-residue collection and processing.** This could include direct engagement with promising hub communities to socialise ideas and identify opportunities; establishing collaborative working relationships between farmers, farm cooperatives, and manufacturers or manufacturing associations; working with third-party aggregators to advance prototypes for fibre production; identifying potential socio-economic and environmental impacts of proposed models; and, developing infrastructure plans for addressing any gaps in existing systems and capacities.
- **Conduct a consumer awareness-building campaign.** Cost projections of well-optimised agro-residue-based textile fibre production are expected to be higher than the existing range in the industry. As in other sectors, like green construction, PV solar, lighting, etc., studies have shown that consumer awareness and sustainability impact campaigns, along with supporting regulations and voluntary commitments, can help support and accelerate the mainstreaming of alternative sustainable value chains in major consumer industries. Science-based targets and consumer awareness can help brands, innovators and manufacturers tip market demand in favour of agro-residue-based apparel.
- **Convene industry and cross-sector policy dialogues.** Activating agro-residue value chains is a cross-sector systems challenge. The research in this report highlights opportunities for industry collaboration and policy development to help address existing barriers. A series of dialogues spotlighting the potential, current state of the field, and recommendations for the future, would help bring more resources and expertise to bear and develop new strategies for tackling or overcoming obvious challenges. Topics could include waste accumulation and aggregation, waste disposal and transportation, farm cooperative models, environmental and climate benefits, and market & commercial guidelines for agro-residue uptake and processing.
- **Decision support tools.** A decision support tool or scenario generator – online, or easily distributable – would help communities, government agencies, manufacturers, innovators and brands interested in agro-residue-based fibres to assess and model different approaches. Such a tool would include standard estimates on labor and logistical costs, residue availability, impurity and yield estimates, etc. Such tools would help demystify agro-residue value chains, and help model possible applications using best practices and standard assumptions. It would also help facilitate community participation and secure community buy-in.
- **Centralised data warehousing, and capacity building.** A series of decentralised deep dive studies would help fine-tune the findings in this report, and dial in specific future prospects for commercialisation (for example, given the prominence of rice husk across the study region, it could form the basis of a deeper-dive study). These studies could be paired with up with specific community and stakeholder capacity building sessions, to close the loop on establishing buy-in and securing environmental benefits and livelihood opportunities.

Box 6.1: Cases of intermediary pulping processors

Kriya Labs, a start-up at the Indian Institute of Technology Delhi, pulps large quantities of rice and wheat crop residues generated after harvesting in the northern states of India. Kriya Labs converts 15-20 million tonnes of rice straw to cellulose pulp annually. This pulp can be used as an intermediary product for industries such as paper, bioethanol, fabrics, and specialty chemicals like cellulose acetate and carboxymethyl cellulose.

Another intermediary BIO-LUTIONS India, purchases a variety of agricultural residues from farmers in Ramangagara, Bengaluru, to make bio-degradable packaging and tableware. Their patented technology converts these residues into self-binding natural fibres through a mechanical process that does not require chemical- or energy-intensive cellulose extraction or bleaching.

Annexures

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Annexure 1
From top crops to most promising agricultural residual sources

Table A1.1: *Top crops in terms of area (ha)*

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Croparea_8_countries [ha]	%area	Accumulated area share
Rice, paddy	11,910,361	2,981,680	44,500,000	15,995,000	2,810,030	1,040,954	10,407,272	7,570,741	97,216,038	30%	30%
Wheat	351,228		29,580,000		8,797,227		1,221		38,729,676	12%	41%
Maize	400,478	123,439	9,200,000	5,680,360	1,318,104	70,895	1,110,944	1,032,598	18,936,818	6%	47%
Seed cotton	15,544	182	12,350,000	5,291	2,372,968	–	2,000	606	14,746,591	4%	51%
Beans, dry	83,340	67,442	13,545,518	191,965	177,335	5,767	106,236	143,492	14,321,095	4%	56%
Chick peas	5,027		11,899,185		976,580				12,880,792	4%	60%
Soybeans	59,445	105,000	11,400,000	723,804	30	1,511	32,000	53,364	12,375,154	4%	63%
Millet	32,651		9,107,000		455,818	6,770		1,862	9,604,101	3%	66%
Rubber, natural	68,438	21,199	456,365	3,671,302		136,875	3,230,242	689,486	8,273,907	3%	69%
Sugar cane	90,155	26,830	4,730,000	416,671	1,101,946	15,732	1,372,169	269,434	8,022,937	2%	71%
Oil palm fruit		14,744		6,777,498			710,103		7,502,345	2%	74%
Rapeseed	307,516		6,700,000		223,402				7,230,918	2%	76%
Coconuts	43,000	13,035	2,098,946	3,247,986	1,417	455,330	194,448	154,684	6,208,846	2%	78%
Groundnuts, with shell	38,044	18,000	4,940,000	353,768	98,639	15,752	30,000	185,899	5,680,102	2%	79%
Pigeon peas	464		5,583,059		5				5,583,528	2%	81%
Sorghum	73		4,960,000		241,456	85	16,614		5,218,228	2%	83%
Vegetables, fresh nes	191,414	105,269	2,583,190	51,002	65,567	6,587	92,463	865,681	3,961,173	1%	84%
Mangoes, mangosteens, guavas	48,947	5,214	2,258,000	235,121	232,837	30,313	427,004	77,689	3,315,125	1%	85%
Cassava		272,172	228,000	697,384		22,360	1,385,817	513,021	3,118,754	1%	86%

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Croparea_8_ countries [ha]	%area	Accumulated area share
Potatoes	477,419		2,151,000	68,683	193,992	5,174	7,639	24,673	2,928,580	1%	87%
Pulses nes	90,179		2,210,202	2,679	3,995		107,328	135,838	2,550,221	1%	88%
Lentils	154,678		2,215,397		13,632				2,383,707	1%	88%
Coffee, green		476	444,256	1,241,514		7,005	43,254	618,879	2,355,384	1%	89%
Fruit, fresh nes	88,571	12,119	1,677,013	103,641	30,514	10,980	36,348	246,365	2,205,551	1%	90%
Sesame seed	37,568	40,000	1,730,000		83,372	11,873	45,000	29,059	1,976,872	1%	90%
Onions, dry	178,506		1,315,000	156,779	150,199	5,492	1,186	101,656	1,908,818	1%	91%
Cashew nuts, with shell			1,003,601	504,317		17,005	14,718	283,986	1,823,627	1%	91%
Cocoa, beans			78,369	1,678,269		2,225	42		1,758,905	1%	92%
Jute	758,248	254	764,359		11		142	125	1,523,139	0%	92%
Fruit, tropical fresh nes	105,944		454,000	196,628	64,535		502,815		1,323,922	0%	93%
Bananas	49,123	31,185	884,000	120,408	30,031		77,028	128,508	1,320,283	0%	93%
Tea	67,045		628,193	113,215		202,540	10,827	116,633	1,138,453	0%	94%
Chillies and peppers, dry	101,072	14,183	781,737		65,275		91,675	70,922	1,124,864	0%	94%
Peas, dry	15,638		997,735		40,355				1,053,728	0%	94%
Oranges	417	11,892	613,000	68,335	137,265	6,840	23,886	97,077	958,712	0%	94%
Spices nes	46,538		887,391	5,086	17,153	583	1,910		958,661	0%	95%
Tomatoes	28,130		786,000	53,850	58,359	6,712	5,190		938,241	0%	95%
Areca nuts	228,371		495,000	154,565		17,877	23,856		919,669	0%	95%
Castor oil seed	380	1,472	900,000	4,522	984		924	8,289	916,571	0%	96%
Anise, badian, fennel, cori-ander			885,435					7,091	892,526	0%	96%
Eggplants (aubergines)			736,000	44,016	8,575	10,834	651		800,076	0%	96%
Tobacco, unmanufactured	42,458	7,526	417,754	203,014	46,331	1,338	19,585	13,463	751,469	0%	96%

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Croparea_8_ countries [ha]	%area	Accumulated area share
Barley	297		661,000		57,582		13,092		731,971	0%	97%
Pumpkins, squash and gourds	27,990		580,244	7,737	26,469	8,469	8,303		659,212	0%	97%
Beans, green	20,594		252,366	122,699	1,716	7,345	167,982		572,702	0%	97%
Peas, green			543,000		26,992		265		570,257	0%	97%
Cloves				561,212		6,354			567,566	0%	97%
Cabbages and other brassicas	18,574		402,000	66,110	4,923	4,202	16,523	36,869	549,201	0%	97%
Okra			514,000		15,713				529,713	0%	98%
Cauliflowers and broccoli	19,459		459,000	12,531	12,620		1,023	7,289	511,922	0%	98%
Pepper (piper spp.)		369	130,870	187,003		43,508	435	107,392	469,577	0%	98%
Sunflower seed			280,000		104,736		31,000		415,736	0%	98%
Garlic	71,414		303,000	5,013	8,699		11,915		400,041	0%	98%
Apples			301,000		88,584				389,584	0%	98%
Sweet potatoes	25,739	8,239	122,336	90,707	1,586	4,099		117,933	370,639	0%	98%
Lemons and limes	22,304	302	286,000		11,937	10,094	14,410		345,047	0%	98%
Chillies and peppers, green			9,634	308,547		13,553	1,435		333,169	0%	99%
Linseed	5,633		320,000		2,821				328,454	0%	99%
Nutmeg, mace and carda-moms			83,618	202,325		870			286,813	0%	99%
Pineapples	14,260	2,385	103,000	14,704		5,543	86,038	45,529	271,459	0%	99%

Source: FAOSTAT, data for 2018

Table A1.2: *Top crops in terms of production of main (food) product (tonnes/year)*

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Production 8 countries [tons]	% production	cumfreq
Sugar cane	3,638,731	594,252	376,900,000	21,744,000	67,173,975	644,785	104,360,867	17,945,204	593,001,814	29%	29%
Rice, paddy	56,417,319	10,647,212	172,580,000	83,037,000	10,802,949	3,929,831	32,192,087	44,046,250	413,652,648	20%	49%
Oil palm fruit		160,000		115,267,491			15,400,000		130,827,491	6%	55%
Wheat	1,099,373		99,700,000		25,076,149		1,351		125,876,873	6%	61%
Maize	3,288,102	604,333	27,820,000	30,253,938	6,308,897	270,041	5,004,125	4,874,054	78,423,490	4%	65%
Cassava		7,646,022	4,651,000	16,119,020		323,108	31,678,017	9,847,074	70,264,241	3%	69%
Potatoes	9,744,412		48,529,000	1,284,762	4,591,776	88,897	125,106	376,377	64,740,330	3%	72%
Vegetables, fresh nes	1,634,000	679,522	34,430,087	515,855	1,074,356	67,884	1,092,313	14,879,631	54,373,648	3%	75%
Oil, palm		32,000		40,567,230			2,776,800		43,376,030	2%	77%
Bananas	810,347	144,403	30,808,000	7,264,383	135,056		1,045,352	2,087,275	42,294,816	2%	79%
Coconuts	466,975	69,365	11,706,343	18,555,371	9,731	2,623,000	885,751	1,571,709	35,888,245	2%	80%
Mangoes, mangosteens, guavas	1,407,308	69,825	21,822,000	3,083,643	2,320,050	516,210	3,791,208	779,347	33,789,591	2%	82%
Onions, dry	1,737,714		22,071,000	1,503,438	2,119,675	107,050	31,035	400,587	27,970,499	1%	83%
Tomatoes	385,038		19,377,000	976,790	550,979	101,404	109,253		21,500,464	1%	84%
Seed cotton	56,809	242	14,657,000	417	4,828,439	-	2,994	330	19,546,231	1%	85%
Fruit, fresh nes	664,103	74,197	10,043,008	1,340,787	174,880	65,870	604,876	2,835,078	15,802,799	1%	86%
Soybeans	98,699	170,000	13,786,000	953,571	29	2,500	56,000	81,348	15,148,147	1%	87%
Oranges	3,315	66,462	8,367,000	2,510,442	1,589,856	56,788	516,426	852,685	13,962,974	1%	88%
Eggplants (aubergines)			12,826,000	551,552	87,587	129,212	19,926		13,614,277	1%	88%
Cottonseed	37,800	174	9,527,000	250	3,151,152	-	2,000	220	12,718,596	1%	89%
Fruit, tropical fresh nes	1,057,143		5,916,000	2,533,498	433,092		2,340,218		12,279,951	1%	89%
Cabbages and other brassicas	321,719		9,035,000	1,407,932	79,804	111,141	264,377	872,767	12,092,740	1%	90%

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Production 8 countries [tons]	% production	cumfreq
Millet	12,713		11,640,000		350,010	8,060		3,370	12,014,153	1%	91%
Chick peas	4,964		11,380,000		323,364				11,708,328	1%	91%
Palm kernels		9,350		10,330,000			645,000		10,984,350	1%	92%
Rubber, natural	6,878	21,872	978,317	3,630,268		82,560	4,744,250	1,137,725	10,601,870	1%	92%
Cauliflowers and broccoli	274,297		8,800,000	152,122	212,431		14,220	140,387	9,593,457	0%	93%
Rapeseed	351,537		8,430,000		260,523				9,042,060	0%	93%
Groundnuts, with shell	66,820	20,000	6,695,000	457,026	97,291	27,602	32,000	456,762	7,852,501	0%	94%
Papayas	131,598		5,989,000	887,591	7,201		176,043		7,191,433	0%	94%
Beans, dry	134,860	86,460	6,220,000	182,706	124,702	6,761	80,619	179,039	7,015,147	0%	94%
Pumpkins, squash and gourds	303,073		5,569,809	454,001	266,137	123,261	120,851		6,837,132	0%	95%
Pineapples	208,401	25,023	1,706,000	1,805,506		34,651	2,113,380	654,801	6,547,762	0%	95%
Cotton lint	18,900	65	4,690,000	125	1,677,287	-	700	110	6,387,187	0%	95%
Okra			6,126,000		120,637				6,246,637	0%	96%
Peas, green			5,430,000		178,231		3,680		5,611,911	0%	96%
Sorghum	87		4,800,000		148,729	169	34,157		4,983,142	0%	96%
Sweet potatoes	246,816	42,953	1,400,281	1,806,389	12,636	43,323		1,374,664	4,927,062	0%	96%
Watermelons			2,520,000	481,744	540,209		162,012	1,200,104	4,904,069	0%	97%
Pigeon peas	465		4,290,000		4				4,290,469	0%	97%
Lemons and limes	67,077	2,898	3,148,000		64,528	316,260	120,177		3,718,940	0%	97%
Cashew nuts, with shell			785,925	136,402		44,756	22,292	2,663,885	3,653,260	0%	97%
Jute	1,613,762	223	1,951,864		12		270	532	3,566,663	0%	97%
Grapes			2,920,000		67,180		82,820	25,165	3,095,165	0%	97%

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Production 8 countries [tons]	% production	cumfreq
Apples			2,327,000		545,875				2,872,875	0%	98%
Chillies and peppers, green			79,668	2,542,358		79,003	19,349		2,720,378	0%	98%
Coffee, green		381	326,982	722,461		6,445	32,684	1,616,307	2,705,260	0%	98%
Chillies and peppers, dry	141,177	13,063	1,808,011		148,114		247,010	101,548	2,458,923	0%	98%
Garlic	461,970		1,721,000	39,302	81,167		74,288		2,377,727	0%	98%
Spices nes	173,079		1,928,708	109,314	77,548	5,465	3,016		2,297,130	0%	98%
Beans, green	134,860		715,141	939,598	7,821	83,966	315,293		2,196,679	0%	98%
Tea	78,150		1,344,827	141,342		303,840	50,614	270,000	2,188,773	0%	98%
Barley	244		1,780,000		55,131		28,288		1,863,663	0%	98%
Lentils	176,633		1,620,000		6,352				1,802,985	0%	99%
Carrots and turnips			583,405	636,873	501,603	71,051			1,792,932	0%	99%
Melons, other (inc.canta-loupes)	227,000		1,231,000	118,708	9,809				1,586,517	0%	99%
Ginger	79,438		893,242	207,412	20	14,208	167,952		1,362,272	0%	99%
Pulses nes	84,831		975,553	1,653	2,939		128,576	115,021	1,308,573	0%	99%
Roots and tubers nes		42,320		422,519	527,436		305,379		1,297,654	0%	99%
Lettuce and chicory	41,003		1,222,571		420		30,763		1,294,757	0%	99%
Tobacco, unmanufactured	89,013	13,856	749,907	181,095	106,727	5,903	67,230	31,440	1,245,171	0%	99%
Castor oil seed	268	1,278	1,198,000	1,711	1,107		903	7,023	1,210,290	0%	99%
Grapefruit (inc. pomelos)	68,137	3,289	257,750				219,838	657,660	1,206,674	0%	99%
Coir	10,321		572,002			159,460	60,559	372,714	1,175,056	0%	99%
Areca nuts	137,043		809,000	128,745		54,691	40,390		1,169,869	0%	99%
Cucumbers and gherkins	110,219		195,768	433,931	68,664	43,942	150,570		1,003,094	0%	99%

Crop	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam	Production 8 countries [tons]	% production	cumfreq
Peas, dry	17,429		920,473		27,123				965,025	0%	99%
Sesame seed	34,859	30,000	746,000		35,699	8,589	31,000	21,250	907,397	0%	99%
Maize, green				590,000			304,833		894,833	0%	99%
Fruit, citrus nes			773,250				14,088		787,338	0%	99%
Tangerines, mandarins, clementines, satsumas	22,086				593,572		139,147		754,805	0%	100%

Source: FAOSTAT, data for 2018

Table A1.3: *Longlist of crops screened in terms of suitability for cellulose pulp and fibre extraction represented in the order of importance per country & in terms of production amount (of main product tonnes/year)*

Top 40+ crops with largest production (tons)	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam
Rice, paddy	1	1	2	2	3	1	2	1
Sugarcane	3	5	1	5	1	4	1	2
Vegetables, fresh nes	6	3	5	31	12	21	11	3
Cassava		2	1	7		6	3	4
Maize/Maize green	4	4	7	4	4	9	5	5
Fruit, fresh nes	12	10	17	19	29		15	6
Cashew nuts, with shell						28		7
Bananas	11	8	6	9	33		12	8
Coffee		31		25		39		9
Coconuts	13	12	14	6	57	2	13	10
Sweet potatoes	21	14	45	15	55	30		11

Top 40+ crops with largest production (tons)	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam
Watermelons			36	32	17		26	12
Rubber, natural	51	19	50	10		18	6	13
Cabbages and other brassicas	17		19	18	42	13	21	14
Oranges	54	13	22	14	11	23	16	15
Mangoes, mangosteens, guavas	8	11	9	11	8	5	7	16
Grapefruits	37	26					23	17
Pineapples	23	18	43	16		31	10	18
Groundnuts, with shell	39	20	23	33	39	32	49	19
Onions, dry	5		8	17	9	14	50	20
Potatoes	2		4	20	6	16	1	21
Coir						10		22

Top 40+ crops with largest production (tons)	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam
Tea						8		23
Beans, dry	28	9	24	41	35	38	37	25
Cauliflowers and broccoli	19		20	44	27		61	27
Soybeans	32	6	12	22	71	44	42	31
Tobacco, unmanufactured	33	21	56	42	38	40	40	32
Sesame seed	44	17	58	87	50	36	51	36
Millet	49		15		22	37		40
Jute	7	33	38	76	73	65	75	41
Seed cotton	40	32	11	63	5		66	42
Cottonseed	43	34	18	66	7		68	43
Cotton lint	47	35	31	67	10		73	44
Chillies and peppers, green	73	22	72	80	84	68	59	62
Sugar crops	20	58	42	56	41	69	40	63
Roots and tubers nes	76	15	88	36	18	74	18	71
Tangerines, mandarins, clem-entines, satsumas	46	75	90	89	13	81	28	78
Dates					20			84
Oil palm fruit		7		1			4	
Fruit, tropical fresh nes	10		27	13	21		9	
Palm kernels		23		8			14	
Beans, green						17	17	
Cereals nes							20	
Papayas	30		26	24	59		24	

Top 40+ crops with largest production (tons)	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam
Pumpkins, squash and gourds	18		28	35	25	12	32	
Lemons and limes	38	27	34			7	34	
Tomatoes	15		10	21	15	15	34	
Sorghum	61		30		30	47	47	
Eggplants (aubergines)			13	30	40	11	58	
Peas, green			29		28		63	
Wheat	9		3		2		70	
Plantains and others						3		
Carrots and turnips					19	20		
Oilseeds nes					14			
Apples					16			
Chick peas		44	16		23			
Rapeseed	16		21		26			
Okra			25		36			
Pigeon peas	57		33		74			
Garlic	14							

Table A1.4: *Crop-residue combinations on longlist characterised according to various parameters*

Crop	Residue	RPR to dm	Total residue [tonnes dm]	% dry in field/ mill	Conversion factor to cel-lulose	Total cellulose [tonnes dm]	Primary resi-due (field)	Secondary residue (mill)	DP (1 >2500, 2<2500)	Type of crop*	Option for vegetable fibre?**
Sugar cane	Trash	0.14	177,900,544	88%	34%	18,145,856	1		1	3	
	Bagasse	0.14	83,020,254	46%	46%	17,567,086		1	1	3	
Rice	Straw	1.25	517,065,810	85%	38%	167,012,257	1		1	3	
	husk or hulls	0.28	115,822,741	90%	37%	38,568,973		1	2	3	
Wheat	Straw	1	125,876,873	85%	43%	46,007,997	1		1	3	
	Bran	0.2	25,175,375	87%	10%	–		1	2	3	
Oil, palm fruit (fresh bunch, incl oil)	Fronds	1.2	276,504,140	40%	30%	33,180,497	1		1	3	
	Petiole	0.05	11,521,006	35%	43%	1,713,750			1	3	
	Empty fruit bunch	0.37	85,255,443	50%	41%	8,974,864		1	1	3	
	Oil palm shell	0.079	8,203,189	85%		–		1	1	3	
	Oil palm mesocarp fibre	0.21	48,388,225	84%	29%	–		1	2	3	
Maize	Stover	0.5	39,211,745	30%	34%	3,999,598		1	2	3	
	Maize cobs	0.5	39,211,745	92%	40%	14,429,922	1		1	3	
Cassava	Cassava stalk	0.2	14,052,848	22%	18%	–	1		2	–	
Bananas+Plantains	Banana fronts	0.14	6,015,388	14%	32%	269,489	1		1	3	1
	Pseudostem	0.15	6,445,058	5%	62%	198,186	1		1	3	1
	Inflorescent	1	42,967,055			–			1	3	
	Rejected fruit	0.15	6,445,058			–			2	3	
Coconuts	coconut husk	0.5	17,944,123	90%	35%	5,652,399	1	1	1	1 & 3	2
	copra cake	0.1	3,588,825	91%	22%	–		1	2	1 & 3	
Mangoes, mango steens and guavas	Mango peels	0.15	5,068,439	16%	16%	–		1	2	–	
	Mango seed	0.3	10,136,877	53%	4%	–		1	2	–	

Crop	Residue	RPR to dm	Total residue [tonnes dm]	% dry in field/ mill	Conversion factor to cel-lulose	Total cellulose [tonnes dm]	Primary resi-due (field)	Secondary residue (mill)	DP (1 >2500, 2<2500)	Type of crop*	Option for vegetable fibre?**
Tomatoes	Stalks and leaves	0.1	2,150,046	5%		–	1		1	–	
Seed cotton	Cotton stalks	3.5	68,411,809	50%	40%	13,682,362	1		1	1	1
	Linter	0.03	586,387	95%	50%	278,534 –	1	1	1	1	1
Soy beans	Straw	2.5	37,870,368	24%	31%	2,817,555	1		1	–	
citrus add: Oranges, tangerines, manderines, lemons, grape fruit	Woody prun-ings	0.1	1,888,858	90%		–	1		1	–	
	Pulp (skin)	0.3	5,666,576	50%		–		1	1	–	
	Pulp (from juice industry)	0.15	2,833,288	50%		–		1	1	–	
Millet	Straw	1	12,014,153	85%	12%	–	1		1	–	
Rubber, natural	Old trees after replanting	0.1	1,060,187	90%		–	1		1	3	
Rapeseed	Stalks	1	9,042,060	85%		–	1		1	–	
Groundnuts, with shell	Groundnut shells	2.5	19,631,253	90%	20%	–		1	2	–	
Pineapple	Leaves	0.25	1,636,941	5%		–	1		1	3	1
Okra	leaves	0.28	1,749,058	5%		–	1		1	3	2
Sorghum	Stalks and leaves	2.62	13,055,832	88%	44%	4,710,544	1		1	3	
Sweet potatoes	Leave and vines	0.5	2,463,531	13%	23%	–			1	–	

* Scoring: 1 Fibre crop textile; 2 Fibre crop other; 3 Fibre plant other primary use

** Scoring: 1 Excellent suitability; 2 Only suitable to produce rough textiles from; 3 Related to fibre plant, but no or little-known technical experience with conversion into textiles from the fibre; 4 New developments, known technical experience with conversion into textiles.

*** cellulose content (% of total dry mass and total cellulose available in tons dm), type of residue (primary or secondary residue), DP value (degree of polymerisation of the fibre in the residue, if DP more than 2500 fibre extraction may be considered for textile generation) and classification of fibre crops according to type* and suitability to be used for vegetal fibre extraction** for textile production.

Annexure 2
From top crops to most promising agricultural residual sources

Table A2.1: *Description of crop production systems for selected crops in eight countries*

Crop selected	Country	Crop production and processing system followed
Sugarcane	India	**Climate:** Sugarcane is a long duration crop, essentially considered as a tropical crop and thus encounters all the seasons, viz. Winter, summer and rainy during the crop cycle. **Soil:** Sugarcane grows best on medium heavy soils, but can also be raised on lighter soils and heavy clays, provided there is adequate irrigation available in the former type of soils and drainage is good in the latter type of soils **Season:** In India, Sugarcane is planted thrice a year, October, Feb-March & July. **Harvesting:** Early varieties have to be harvested at 10 to 11 months age and mid-season varieties at 11 to 12 months age **Plant part used as a food:** The stem is an excellent source of sugar and is very nutritious
Sugarcane	Thailand	**Climate:** Climate change can directly affect crops through rising temperature and changing rainfall patterns, or indirectly affect crops through soil, nutrients, and increasing pest interference. Studies revealed that crop yields have been affected by the variability of temperature, rainfall, and the interaction between them and climate change impacts will be different across locations, types of crop, scenarios, and farmer adaptation (Raymundo et al.2018) **Soil:** For a crop like sugar cane, soil water stress will invariably result in reduced growth and yield. Soil needs to be conserved and nourished. Sugarcane is well grown in loam, clay loam, or sandy loam. The topographic area may be sloped, and hilly that may cause high erosion by forces of rain and wind. Furthermore, sugarcane requires a big plantation. In such conditions, there is a need for conservation and nourishment to sustain soil fertility (GAP, 2010). **Season:** Sugarcane farmers in the Northeast region generally plant their cane in October and November, and in the Eastern Central Plains region, November to February. Planting in the irrigated area of the North region is December to April and May to June in the rain-fed area. In the Western Central Plains area, planting in irrigated areas is from January to March and in the rain-fed area May to June. While the sugarcane crop calendar varies by region, the growing period is about 10-14 months depending on the variety of cane (FAO, 1997a). Harvesting: Sugarcane is harvested from November to March in Thailand.
Sugarcane	Thailand	Sugarcane shall be harvested at the age of not less than 10 months or the Degree Brix of juice is not less than 20 degree Bx. **Plant part used as a food:** The stem is an excellent source of sugar and is very nutritious. Cultivation of sugarcane crop is carried out for crushing purpose to obtain sugar, Panela (Jaggery, gur) and other products. By-products like alcohol used in the pharmaceutical industry, ethanol used as a fuel, bagasse used for paper-making and chipboard manufacturing and press mud used as a rich source of organic matter that adds to soil fertility are derived after the cane is crushed.
Sugarcane	Pakistan	**Climate:** Sugarcane cultivation requires a tropical or subtropical climate, with a minimum of 600 mm annual rainfall. In Pakistan sugarcane is cultivated in three ecological zones i.e. north western, central and southern zones. Climatic conditions of lower Sindh (southern) are more favourable having hot and semi-humid climate. **Soil:** Sugar cane can be grown successfully on a great variety of soils. Sugarcane is a deep-rooted crop and proper soil preparation plays an important role in the development of the cane root system, and achieving optimal growth of the crop. The land should be prepared by deep ploughing at least after every two years. The soil should be disked (valleyirrigationpakistan.com). It is very important that well-rotted farmyard manure (FYM) should be applied a month prior to land preparation. Press mud from the sugar industry is another excellent source of organic matter and nutrients. **Season:** There are mainly two planting seasons for sugarcane: fall and spring. Fall planting starts from the first week of September and continues to mid-October in the Punjab and Sindh, while in the NWFP planting is done in October and November. Spring planting starts from mid-February and lasts until the end of March in Punjab and Sindh (Qureshi and Afghan, 2005). **Harvesting:** The harvesting period follows the pattern of many other northern hemisphere crops, beginning in November/December and ending in April/May. Punjab and NWFP mostly plant in spring, and harvest 8 to 10 months later (FAO, 1997b). **Plant part used as a food:** Stem
Rice	Bangladesh	**Climate**: The uneven topography and humid tropical climate of Bangladesh with abundant monsoon rain offers a unique environment for the rice plant. Aman crop experiences two extreme climates at two ends the period between April to August experiences higher temperatures with minimum diurnal fluctuation, moderate humidity during the reproductive stage, but with occasional scanty rainfall during the early vegetative growth period. Such a climate is very much conducive to higher vegetative growth of the crop with the lowest partitioning coefficient and development of pests and diseases.

Crop selected	Country	Crop production and processing system followed
Rice	Bangladesh	**Soil**: The crop can be grown in a wide range of climatic and soil conditions, provided water is available, it has the widest adaptability to different soil types. Season: There are three rice-growing seasons in Bangladesh: aus, aman, and boro. Aus is the pre-monsoon upland rice growing season under rainfed conditions. The monsoon-season rainfed rice is the aman, which is the most widespread, including along the coastal areas. Boro is the dry-season irrigated rice planted from December to early February. **Harvesting:** The largest harvest is aman, occurring in November and December and accounting for more than half of annual production. Some rice for the aman harvest is sown in the spring through the broadcast method, matures during the summer rains, and is harvested in the fall. **Plant part used as a food:** Rice milling is a process by which the husk is removed, and further produces an edible, rice grain that is sufficiently milled and free of impurities. If only the husk is removed then 'brown' rice is the product. If the rice is further milled or polished then the bran layer is removed to reveal 'white' rice.
Rice	Cambodia	**Climate:** Rice is the most important crop and accounts for 80% of Cambodia's total agricultural production (Dek et al, 2017).Rice in Cambodia is grown in lowland rainfed, irrigated, upland rainfed, and deepwater ecosystems (Cosslett and Cosslett, 2018). Lowland rainfed rice is produced across all provinces. Soil: The two broad types of rice soils in the lowlands are: a) old alluvial and colluvial plains which account for 67% of the lowland rice area and are generally light-textured soils of low fertility used for rainfed wet season rice. b) soils in the active floodplains around the Tonle Sap Lake and the Mekong and Bassac Rivers that account for 30% of the rice area. These soils are heavy-textured and fertile, being formed from fresh alluvium deposited by annual floodwaters. They are submerged for three to five months of the year and are commonly used for deep-water rice and recessional/irrigated Dry Season rice (White et al. 1997). **Season:** Cambodia has two rice crops in a year. The major monsoon (long-cycle) planting season falls in late May through July. For the heavy rain wet climate, rice shoots are transplanted during summer months through September. The annual flooding of the Mekong during the rainy season deposits a rich alluvial sediment that accounts for the fertility of the central plain and provides natural irrigation for rice cultivation. **Harvesting:** Crops are manually harvested and tied into sheaves. These sheaves are placed on top of the standing stubble or transported to a central threshing site where they are dried for 2-3 days. Depending on locality, threshing is done at a central site in the field or in the village. The main harvest occurs for Short life rice (3months old) is in Aug/Sept and Long-life rice (6months old) in Dec/Jan. **Plant part used as a food:** Grain - Sticky rice - known as sweet rice or glutinous rice, Red rice or brown rice - a type of unpolished rice that has higher nutritional value and white rice.

Crop selected	Country	Crop production and processing system followed
Rice	India	**Climate:** In India rice is grown under widely varying conditions of altitude and climate. Rice crops need a hot and humid climate. It is best suited to regions which have high humidity, prolonged sunshine and an assured supply of water. The average temperature required throughout the life period of the crop ranges from 21 to 37º C. Soil: Rice can be cultivated in wide varieties of soils such as silts, loams and gravels. Deep fertile clayey or loamy soils are best suited for rice cultivation **Season:** In India, rice is mostly cultivated in Kharif season i.e., June to October. Depending upon the water availability it can be grown in Rabi (Oct-Jan) and summer (Jan-May) season as well (FAO, 1997c). **Harvesting:** Normally short duration varieties take 100-120 days, medium duration 120-140 days, and long duration +160 days to harvest **Plant part used as a food:** Grain
Rice	Indonesia	**Climate:** The Indonesian Ministry of Agriculture has developed a tool called "Integrated Cropping Calendar System (KATAM)" to support in increasing food production and helping farmers to adapt to the changing climate (Riga, 2016). Most of Indonesia has a moist tropical climate, with abundant rain and high temperatures. Rice production is heavily concentrated on the islands of Java and Sumatra. Rice is grown year-round, with some farmers being able to grow three crops a year, but it is common to grow two rice crops a year. **Soil:** Rice is cultivated in both lowland and upland elevations throughout Indonesia, with the upland crop typically being rainfed and receiving only low levels of fertilizer applications. Irrigated lowland rice is both well-watered and heavily fertilized. The nutritional requirements of the rice crop and the availability of nutrients in soil and irrigation water is calculated to ensure the proper amount of fertilizer for each field. (International Nature Farming Research Center, 1988) **Season:** There are three rice growing periods or seasons in Indonesia, a single wet season crop followed by two dry season crops. **Harvesting:** Rice is planted and harvested twice a year in Ubud. Planting seasons are from January to February and July to August. Harvesting takes place from April to May and October to November. Approximately 45 percent of total production is usually from the wet season crop, cultivated from October to December and harvested from March through April (IPAD, 2016). **Plant part used as a food:** Grain. Indonesians typically eat steamed long-grain rice with their meals (sticky rice is usually used for desserts or sweet snacks). Indonesian rice isn't exported, but jasmine or other long-grain rice may be substituted.

Crop selected	Country	Crop production and processing system followed
Rice	Pakistan	**Climate**: Pakistan is considered amongst the highly vulnerable countries under the impact of climate change due to its varied demographic and topographic structure. Climate plays a holistically significant role for agricultural productivity. The rice crop, grown in mild temperature with standing water in paddy fields, is already under heat stress and further rise in temperature may affect the crop badly (PIDE, 2016). **Soil:** Punjab is the largest rice-producing province and the famous Basmati rice is produced between the Ravi and Chenab rivers. Rice is planted only under irrigated conditions and three methods of land preparation for rice are used for the production purpose: complete puddling, partial puddling, and dry land preparation, depending upon the availability of water, soil type, and farm implements. Rice is cultivated in many different climates and on a wide range of soils, with tremendous differences in soil properties. **Season:** "Kharif "and "Rabi" are two agricultural seasons in Pakistan. The kharif season falls in the summer growing period from May to November, with one of the major crops cultivated being rice. The rabi or winter growing season runs from December through April. H**arvesting:** Rice crop is mainly rainfed and it is planted in the months of May-June during the kharif season. The annual rice harvesting occurs from October-December. **Plant part used as a food:** There are various types of rice created during the growing and threshing of grains such as Kernel rice, Super Kernel, Irri-6, Basmati, Saila, Tota, etc
Rice	Sri Lanka	**Climate:** Sri Lanka exemplifies a variety of climatic conditions depending on the geographical settings of respective locations. In Sri Lanka, rice is grown under a wide range of physical environments such as different elevations, soils and hydrological regimes. There is a wide range of climatic and soil conditions in the country. There are 7 major AEZs based on rainfall and elevation, which are further subdivided into 24 agro-ecological regions, considering the rainfall distribution, soil type and the landform, where rice is produced (Papademetriou et al. 2000). **Soil:** Soils with a sulfuric horizon or sulfidic materials within 50 cm of the soil surface are not considered suitable for rice production. Alluvial soils are reddish to brownish in colour, moderately fine textured and imperfectly to poorly drained. These soils majorly occur in the flood plains and these soils are generally deep. They are more suitable for rice cultivation. **Season:** Based on inter-monsoon rain fed systems with the Northeast monsoon, the major cultivation season (Maha) begins from late September to early March. The minor cultivation season (Yala) based on an irrigated system, begins from early April to early September, bringing rain mostly to the Southwest region of Sri Lanka. Farmers are encouraged to follow a uniform cultivation calendar, as correct timing in planting and harvesting within the season, reduces the risk of terminal drought and pest and disease incidences.

Crop selected	Country	Crop production and processing system followed
Rice	Sri Lanka	**Harvesting:** According to the GAIN Report 2019, the Maha crop is typically harvested in March/April and provides about 60 to 65 percent of Sri Lanka's annual rice production. The Yala crop is typically harvested in August/ September and provides 35 to 40 percent of Sri Lanka's annual rice production. **Plant part used as a food:** Across the country, varietal preferences include both long grain and short grain rice, raw or boiled form, in white or red pericarp. Long grain raw rice (non-parboiled) is the most-consumed type.
Rice	Thailand	**Climate:** Rice production in Thailand can be classified into four ecosystems; irrigated, rainfed lowland, deepwater, and upland. Rainfed lowland is the most predominant, followed by irrigated, deepwater, and upland. The major production constraints are rainfall variability, drought, submergence, and inherently low soil fertility (FAOSTAT, 2012). **Soil:** Most of the non-aromatic white rice for the domestic and export markets is produced in the irrigated areas of the Central Region, whereas most of the fragrant KDML105 rice is produced under rainfed conditions in the Northeast. Most paddy land is rainfed and can only support a crop of rice in the wet season (May to October). The Rainfed lowland rice are cultivated in the shallow depressions with more clayey soils, called the lower paddies (Wada, 2005). **Season:** Rice is grown in all provinces of Thailand. More than 50 percent of the total rice growing areas are in the northeast region, but the Central Plains is known as the "rice bowl" of Thailand (FAO, 2002). In northern and northeastern regions, the main rice season lasts from May to December, while in the southern region, the main rice crop lasts from September to May. **Harvesting:** The rice-planting season in Thailand usually starts in May. The rice enjoys the rainfall during the monsoon season through till September. The rice turns from emerald, to a darker green and finally to dry gold under the strong sun. Rice is ready to be harvested by November end. **Plant part used as a food:** The vast majority is rainfed rice, grown only in the wet season; the rest is irrigated, with small amounts of dry-season production. The most well-known variety is Jasmine rice, a long-grain, flowery smelling rice.

Crop selected	Country	Crop production and processing system followed
Rice	Vietnam	**Climate:** Climate change repercussions and damages to rice agro-ecosystems can be severe on the large extent of acid sulfate soil in the Mekong River Delta and the Red River Delta (AIDA, 2017). **Soil:** The Mekong River Delta produces most of Vietnam's rice. Soils in the Mekong River Delta are highly variable, but alluvial, acid-sulfate, and saline soils dominate. Alluvial soils predominate in 30% of the Mekong Delta, mostly along the banks of the Tien (Mekong) and Hau (Bassac) rivers. Floating rice is grown in the low-lying zone in the upstream of the Vietnamese part of the Mekong river. Heavy clay soils in the floating rice fields are prepared in dry condition, therefore they are generally not puddled during the early part of rice growth. **Season:** The Mekong Delta climate is governed by the hot monsoon. Rice is planted in three seasons: Mua (or monsoon), He-Thu (or Summer-Autumn) and Dong-Xuan (or Winter-Spring). The areas under Dong-Xuan and He-Thu crops have been increasing while that of Mua have been reduced significantly, especially in the Mekong River Delta. The rice growing seasons are known as the Winter-Spring (WS) and Summer-Autumn (SA) season. **Harvesting:** Sapa is in the harvesting season (September and October) in Vietnam. At that time, rice is ripe, getting yellow in autumn sunshine and begins to drop. Harvesting floating rice is a tedious task. It is harvested panicle by panicle. As the water level goes lower and lower, the panicles recline gradually, and finally the entire plant lays on the mud, which is followed by picking and cutting of panicle, loading, drying and thrashing. **Plant part used as a food:** In Vietnam, rice has long been a strategic crop for national food security. White rice is prepared in a variety of ways in both savory and sweet Vietnamese dishes.
Wheat	India	**Climate:** Wheat is a widely adaptable crop that can be grown in climates ranging from temperate to tropical and cold northern parts. Places with cool, moist weather for most part of the year followed by a short, dry and warm spell is most suited for wheat cultivation. **Soil:** Soils with a moderate amount of water holding capacity. Generally, black cotton soil with good drainage capacity and a neutral pH is preferred for cultivation. **Season:** Wheat, in India, is best grown as a rabi or winter season crop since the conditions during that time are conducive for growth and ensures maximum yield. **Harvesting:** Harvesting is usually done manually with a sickle although for vast areas, machines may be used. The crop is then threshed using a thresher. **Plant part used as a food:** Grain

Crop selected	Country	Crop production and processing system followed
Wheat	Pakistan	**Climate**: Wheat yields have undergone a huge shift since the year 2000 due to climatic uncertainties. Higher temperature together with reduced soil moisture decreases the season's length of crop growing which alters the plant growth stage and affects the partitioning and quality of biomass causing yield reduction (Hakim et al. 2012) **Soil:** Wheat cultivated areas in lower Sindh are located in the irrigated plains which are fed by fertile alluvial soils deposited by the Indus River. It has a hot and arid climate whereas the climate of central and southern Punjab is categorized as dry semi-arid agro-climate, a highly productive agricultural zone due to fertile soils and well-managed canal irrigation system which contributes to almost 75% of the total production in Pakistan. **Season:** The Kharif, with a sowing season from April to June and harvest in October to December; and the Rabi, which begins in October to December and ends in April to May. The marketing year for wheat in Pakistan runs from May to the following April (FAO, 1997). **Harvesting:** After manual harvesting, wheat is threshed using tractor-powered threshers. The moisture content of wheat at harvest is usually about 10 percent, therefore the procurement and transportation can start immediately after harvest, without waiting for grain to dry. The government usually releases the wheat to millers from early October until the next harvest in April/May. **Plant part used as a food:** Wheat grain is used as Pakistan's dietary staple.
Sorghum	India	**Climate**: Sorghum is a warm temperate and tropical cereal. It is grown from sea level to as high as 1500 metres. The kharif sorghum areas extend from 9^{0}N to 25^{0}N latitudes while the rabi confines to the narrow belt of 14^{0}N to 21^{0}N latitudes (Ministry of Agriculture & Farmers Welfare, 2016). **Soil:** It adapts to a wide range of soils but grows well in sandy loam soils having good drainage. Soil pH range of 6 to 7.5 is ideal for its cultivation and better growth. The rabi season sorghum is grown on residual and receding soil moisture on shallow and medium-deep soils (ICAR, 2016). **Season:** Sorghum/Jowar is grown in the kharif/ rainy season) as well as the rabi (post rainy) season. The production and cultivation during kharif is higher. The crop grown during Rabi is mostly used for human consumption whereas kharif crop is not very popular for human consumption and largely is used for animal feed, starch, and alcohol industry. **Harvesting:** In case of single cut varieties, the crop gets ready for harvesting in 65 to 75 days after sowing (50%, flowering stage). In case of multi cut varieties, the first cut should be done within 45-50 days and subsequent cuts should be carried at 1-month intervals. **Plant part used as a food:** Grain. It is a cereal crop grown in the semi-arid tropics of the world providing food, feed, fodder, fibre and fuel.

Crop selected	Country	Crop production and processing system followed
Oil Palm	Indonesia	**Climate:** With high rainfall (minimum 1600 mm/year) and a tropical climate within 10 degrees of the equator, the east coast of Sumatra is the most suitable area for growing Palm oil (Budidarsono, 2013). There are negative consequences of land conversion and deforestation on biodiversity and temperature due to plantation of Palm oil. **Soil:** Palm oil production is land-intensive, and much of Indonesia's rainforest had been cleared to make way for plantations for palm oil. In core smallholders, palm plants are cultivated on mineral soils, therefore the largest composition of land used is mineral soils compared to peatlands. **Season:** The oil palms usually take 2.5 to 3 years after the plantation in the main field to be ready for harvest. Determining harvesting time is very important in oil palm cultivation as it greatly impacts the quality and quantity of oil. **Harvesting:** The young palms begin to produce the first harvestable fruit bunches after 30-36 months in the field. Peak harvest occurs from years 8 to 15. The economically viable lifespan of an oil palm is typically 22 to 25 years depending upon oil price, economically harvestable height, and yield. The 25 feet height is an industry limit which is based loosely on the height of the average harvester plus the length of the long sickle harvesting pole (IPAD, 2016). **Plant part used as a food:** Palm oil is extracted from the fruit of the oil palm tree. Itis an important plantation crop-producing food oil, industrial oil, and biofuels
Oil Palm	Thailand	**Climate:** Oil Palm thrives in wild, semi-wild and cultivated areas in the regions of equatorial tropics. The tree requires a deep soil, a relatively stable high temperature and continuous moisture throughout the year. **Soil:** Oil Palm thrive best in well- drained deep loamy moist and alluvial soils rich in organic matter. These trees require at least 1 meter soil depth. Most of Thailand's palm oil is grown in the southern part of the country. In one protected area, called Pru Kachin, oil palm is grown in peatlands, for which the swampy peat must be drained – which releases carbon into the atmosphere and makes the forests that overlay them more susceptible to fire. **Season:** The oil palm requires an evenly distributed annual rainfall of 1500 - 2000 mm or more, without a defined dry season. Best oil palm yields are obtained in those places where there is a maximum average temperature of 29°C - 33°C and a minimum average temperature of 22°C - 24°C. **Harvesting:** Oil palm normally harvests all through the year Plant part used as a food: Palm oil extracted from the fruit, is used in a wide variety of products such as food items (cooking oil, margarine, sweet), commodities (cosmetics, soap, candle), and alternative fuel source-biodiesel. (Phitthayaphinant et al. 2012)

Crop selected	Country	Crop production and processing system followed
Maize	India	**Climate**: Maize is cultivated on nearly 150 m ha in about 160 countries having wider diversity of soil, climate, biodiversity and management practices. **Soil:** Variety of soils ranging from loamy sand to clay loam can be used to grow maize. However, soils with good organic matter content having high water holding capacity with neutral pH are considered good for higher productivity in India (farmer.gov.in). **Season:** Maize can be grown in all seasons such as Kharif (monsoon), post monsoon, Rabi (winter) and spring. During Rabi and spring seasons to achieve higher yield, irrigation facilities are required (Parihar et al. 2011). **Harvesting:** Maize grows best in fertile well irrigated, medium, heavy loamy soil. It is also commonly grown in the carse ravel soils of hilly maize tracts. In India the maize crops are generally sown in June-July and harvested in September-October. **Plant part used as a food:** maize can be consumed directly or used for corn ethanol, animal feed and other maize products, such as corn starch and corn syrup. The six major types of maize are dent corn, flint corn, pod corn, popcorn, flour corn, and sweet corn.
Maize	Indonesia	**Climate:** The tropical and wet climate of Indonesia is favourable to grow multiple crops in the same piece of land within the same year. Average temperature is around 26-28°C, with total annual rainfall ranging from 1,000 mm in East Nusa Tenggara and Palu Valley to more than 3,000 mm in most parts of Sumatra, South Kalimantan, West Java, Central Java, and South Sulawesi. **Soil:** The maize ecozones are divided into four: Java and Bali, Sumatra, Sulawesi and Nusa Tenggara, and Kalimantan (Swastika et al. 2004). Indonesia is home to the volcanic soil, which has been scientifically proven to be rich with the necessary nutrients needed by plants to grow. The regular PH level of around 2-7 is the perfect condition for plants to grow. **Season:** Maize can grow in regions with consistent weather that ensures the sustainable supply of sunlight and water. Indonesia's first maize season normally takes place from October to February followed by the second season which takes place from March to June, while the third runs from July to September (GAIN Report, 2019). **Harvesting:** Java, the main maize producing area in Indonesia, followed by Sulawesi, Sumatera, and Nusa Tenggara. **Plant part used as a food:** In some provinces, such as East Java, East Nusa Tenggara (NTT), North Sulawesi, South-East Sulawesi, and Irian Jaya, maize is consumed as a staple food.

Crop selected	Country	Crop production and processing system followed
Banana & plantain	India	**Climate:** Banana is a tropical plant requiring a warm and humid climate. Banana requires on an average, 1700mm rainfall distributed throughout the year for its satisfactory growth. **Soil:** Deep soils with good drainage, rich loamy and silty clay loam soil with pH between 6-7.5 is most preferred for banana cultivation. Ill drained, poorly aerated and nutritionally deficient soils are not suitable for bananas. Extreme clayey, Sandy soil, Saline soil and Calcareous soil is not suitable for Banana cultivation. **Season:** Banana plantation can be done in April-May or September-October **Harvesting:** The dwarf banana varieties are ready for harvest within 11-14 months after planting, while tall cultivars take about 14-16 months to harvest. A bunch usually takes 90-120 days to mature after shooting. **Plant part used as a food:**Fruits
Coconut	India	**Climate:** Coconut is a tropical crop and grows well in a hot climate. Temperature is an important weather factor that has great influence on the growth and productivity of the coconut palm as it requires plenty of sunlight. As per the Tamil Nadu Agricultural University, a mean annual temperature of 27 degree C is best for vigorous growth and good yield. **Soil:** Coconut is grown in different soil types such as laterite, coastal sandy, alluvial, and also in reclaimed soils of the marshy lowlands. It tolerates salinity and a wide range of pH (from 5.0-8.0). Imperfectly drained soil, shallow soils with underlying hard rock, low-lying areas, and heavy clay soils are not suitable for coconut cultivation. **Season:** The fruit of the coconut palm is harvested at different stages of maturity. For copra, it is harvested fully ripe at about 11 to 12 months when the husk has turned brown. For coir, it is picked at least a month earlier, when the fruit is still green. **Harvesting:** The harvesting period in Tamil Nadu and Karnataka lie between February to August, while in case of Kerala, it is December to May. The seed nuts are harvested during April-May which are planted in June in the west coast region, whereas sowing is done in October – November in the East Coast region. **Plant part used as a food:** Flesh and water
Coconut	Indonesia	**Climate:** The locations of coconut are scattered almost evenly throughout the country islands mainly in Sumatera, Java, Sulawesi, Bali, West Nusa etc. **Soil:** The coconut tolerates a very wide range of soil conditions, from the almost pure coral found on atolls, to peats and acid swamps. Clayey soils are not suitable for coconut production. **Season:** The coconut palm can grow and bear fruits with a well distributed rainfall of 100 cm but for profitable cultivation, 100 cm to 225 cm per annum, evenly distributed throughout the year are necessary. Coconut plants require an even amount of rainfall throughout the year of 2500-3500 mm (Y Matana et al. 2020).

Crop selected	Country	Crop production and processing system followed
Coconut	Indonesia	**Harvesting:** Coconut includes annual crops that bear fruit throughout the year. Coconut trees entering productive age can produce 12–15 bouquets a year, which means that a coconut tree produces a wreath almost every month (Simpala et al., 2015). Coconut is harvested by farmers by climbing trees using hands or notches on tree trunks as a foothold. Farmers used machetes to cut ripe coconuts from bunches. The harvested fruits were then grouped according to their age. **Plant part used as a food: T**he white, fleshy part of the coconut seed is called coconut meat. Coconut water is high in potassium and sugar which makes it a great drink.
Pineapple	India	**Climate**: Pineapple is suitable for cultivation in humid tropics. The fruit grows well near the sea coast as well as in the interior; so long the temperatures are not extreme. It grows well, both in the plains and also at elevations of 900-1100m above sea level. It tolerates neither very high temperature nor frost. The optimum temperature required for successful cultivation is 220-320 °C. The cultivation of pineapple is confined to high rainfall and humid coastal regions in the peninsular India and hilly areas of north-eastern region of the country. **Soil:** Pineapple grows in almost any type of soil, provided it is free-draining. Slightly acidic soil with a pH range of 5.5 to 6.0 is considered optimum for pineapple cultivation. The soil must be well drained and light in texture. Heavy clay soil is not preferred. It can grow in sandy, alluvial or laterite soil. **Season:** Areas with heavy rainfall are best for pineapple growth. Optimum rainfall is 1500 mm per year although it can grow in areas having 500 mm to 5550 mm of rainfall. **Harvesting:** Pineapple plants flower 12-15 months after planting and the fruits become ready 15-18 months after planting depending upon the variety, time of planting, type and size of plant material used and prevailing temperature during the fruit development. Under natural conditions, pineapple comes to harvest during May-August. The fruit usually ripens about 5 months after flowering. Irregular flowering results in the harvesting spread over a long period. Most common varieties grown in India are - Kew, Giant Kew, Queen, Mauritius, jaldhup, lakhat etc. (icar.gov.in) **Plant part used as a food:** Pineapple core and flesh
Pineapple	Indonesia	**Climate:** Pineapple cultivation is plannable, which is one of its major characteristics. Depending on the pedoclimatic conditions, it is possible to organise continuous year-round production. Moreover, the choice of starting plant stock makes it possible to predict the fruit size upon harvesting; generally larger for industrial applications. **Soil:** Quality of pineapple varies due to cultivation technique, growing environment and variety. Good quality pineapple grows well in acidic loams, sandy loams and clay loams soils under warm and humid climate with sunny days and cool nights (Hossain, 2016).

Crop selected	Country	Crop production and processing system followed
Pineapple	Indonesia	**Season:** Indonesia has a dry season in which irrigation activities are needed to grow plants. Irrigation on pineapple plant is very important because it affects the growth and production (Cahyono et al. 2018). **Harvesting:** One of the pineapple varieties In Indonesia is called the 'Nanas Palembang' and as the name suggests is grown in the area around Palembang - capital of South Sumatra. For this variety of Indonesian pineapple, the bumper harvest times are during the months of December, January and July. **Plant part used as a food:** Flesh
Pineapple	Thailand	**Climate:** Thailand has the right range of temperature and the type of soil to grow pineapples. They can grow well in the temperature ranging from 23.9 °C to 29.4 °C with rainfall ranging from 1,000-1,500 ml per year. **Soil:** The types of soil that are good for pineapples are loose loam, sand loam, gravel soil, and seashore soil. The plantation areas are mostly low plain with a mixture of loose and sandy soil. Most farmers rely on natural water resources and small numbers employ water irrigation during a period of drought. **Season:** A crop of pineapples can be grown to maturity at any time of the year, with suitable size of plants, planting time and flower induction, but the physical characteristics and eating quality vary widely with seasons. The crop harvested in summer has the highest fruit weight and the fruit is mainly conical in shape with a rosette crown, while most of fruits harvested in the rainy season and in winter crops are cylindrical and spherical with elongate crowns (Joomwong and Jinda , 2005). **Harvesting**: In Northern Thailand pineapple is harvested three times per year in the summer, rainy season and winter. Fruits were harvested 110-160 days after full bloom (DAFB) during different crop seasons. **Plant part used as a food:** Flesh
Pineapple	Vietnam	**Climate:** Pineapple requires areas where the climate is warm, humid and free from extreme temperatures (25 °C being the optimal temperature). The fruit is grown all year round, although the sweetness of the fruit varies depending on various conditions. **Soil:** The fruit takes longer to grow at higher altitudes and latitudes, where temperatures are lower. Pineapple must have an acid soil with pH around 4-5 or it will not grow successfully. Fertile soils are not required, provided nutrients are added (FAO, 2004). **Season:** The pineapple is mostly cultivated in the tropics between 25°N and S. Temperature range of growing areas is 23 to 32°C. Pineapple cannot tolerate frost, and high temperatures, and fruit is sensitive to sunburn, but can withstand considerable drought. Continuous warm conditions favour rapid growth and development.
Pineapple	Vietnam	**Harvesting:** The fruits are harvested when their eyes turn yellow. Fruits can be harvested all year round although the plant can be forced to flower almost any time of the year, depending on climates, through the use of a chemical (ethylene and other inductants) in order to facilitate harvesting. Average weight of fruit varies from 600 – 800 g. CAYENNE pineapple (Smooth Cayenne' or 'Cayenne', 'Cayena Lisa') is the second most popular pineapple in Vietnam, planted & harvested mostly in Tam Diep (Ninh Binh), Quynh Luu Nghe An), Dac Lac, Don Duong (Lam Dong). **Plant part used as a food**: Flesh
Okra	India	**Climate:** Okra grows best within a temperature range of 24-27°C, as it gives good yield in warm humid conditions (Kumar & Choudhary 2014). **Soil:** Sandy loam and clay-loam soils are best for Okra cultivation in India. The optimum pH range lies between 6 and 6.8. Soils with high organic matter are preferred. Okra can also be grown in mild salt affected soils. **Season:** It requires a long warm growing season during its growing period. Depending on the region, the crops are sown between January-March or June-August. **Harvesting:** Crop is harvested in 55 to 65 days after planting when pods are 2 to 3 inches long and tender. The summer crop is sown during February–March and harvested between April–June. **Plant part used as a food:** Pods, Leaves and Flower
Okra	Pakistan	**Climate:** Okra is a warm season, kharif crop which requires high soil temperatures for best production. **Soil:** The type of soil and preparation methods, time and method of sowing, seed quality, irrigation and fertilizer applications, inter-culturing etc plays a pivotal role in Okra production. Well drained-sandy loans (high in organic matter) are the most desirable, as Okra grows best in neutral to slightly alkaline soils with 6.5 pH. **Season:** The yield of okra varies from 8 to 10 t/ha. of green fruit during summer and 10-12 t/ha in the rainy season (Khalid, 2015). **Harvesting:** Farmers start their cultivation from during the off season i.e. January. Okra generally takes two months for harvestable pods, which extends from February through November, but most of the production occurs in the summer months. **Plant part used as a food:** The leaves of the okra plant are eaten raw in salads. The flowers and pods are eaten as vegetables.

Annexure 3
Review of competing uses of selected agricultural biomass sources

The most common use and management practices followed with the shortlisted residues was determined by using a combination of primary information (from stakeholder consultations with farming experts) and secondary information based on literature review on the crop production systems in the eight countries, specifically for the main production regions for the selected crops. This information has been used to describe the competing uses situation in the Table A3.1. The classification is determined in terms of high, medium and low availability of unused potential which influenced the further selection of the residue for hub location identification and further cost assessment in this study. Some of the key insights on the competing uses:

- For sugarcane trash and bagasse, the availability of the unused potential is expected to be between 20% and 40% in the two main production regions in India. For bagasse it can be expected that there is a smaller unused potential than for the trash. Therefore, the sourcing of cellulose extraction plants will be reviewed with both a combination of trash and bagasse. Besides this, the bagasse demand for alternative uses, such as for cellulose extraction for textiles, in a region should not become too high as this will increase the price and it may lead to an increase of fossil energy to replace the bagasse-based energy demand of sugar mills.
- Based on the findings it was indicated that the competing uses for straw is limited in all the countries because it is not significantly used as a feed for livestock and it decomposes very slowly in the soil. Therefore, straw as residue is often difficult to dispose of in time for the next season or crop. This is further complicated by the fact that in many rice producing regions, machinery is missing to harvest the grains and the straw in combination. Therefore, burning the residue even though banned in many countries, is still the most viable option for many farmers. In India however, the information in the table below confirms a relatively large unused potential for rice straw in the Punjab and Uttar Pradesh regions, but not in West Bengal. The identification of the hub location for rice straw based cellulose extraction will therefore be focused on the first two regions and not in West Bengal.
- For maize and sorghum stover/straw, as indicated it seems that these residues have a high competing use and that the likely unused potential is very low. It is therefore logical to exclude them from the hub location assessment for cellulose extraction.
- For wheat straw alternative uses are also large. Basing a full cellulose extraction mill on it would not be recommended. However, in combination with a rice straw cellulose extraction chain will be reviewed in India, where in the Punjab region it is very common to grow rice in rotation with wheat. By combining both straw sources security of supply in the chain may be increased. The wheat straw demand will need to remain modest as compared to rice straw though given the much larger unused rice straw potential.

Table A3.1: *Current competing uses per shortlisted residue and likeliness for large unused potential*

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Sugarcane	Trash	India	To maintain soil nutrients a share of trash is needed. The quantity depends on soil and climate conditions. It is estimated that about 3 tons of trash per hectare should be left behind which would be around 20%-30% when an average per hectare yield of between 10-15 MT cane is assumed for most regions in India About 30% of the trash is taken to the sugar mill together with the cane. So about 40% of the trash remains. A small fraction of this is fed to animals, but mostly it is burned in the field (with high GHGs emissions and an important source for fine particles and smog). So according to Kumar et al. (2017) there is 28 million tonnes of unutilised trash, which is now still burned in the field. Of this trash almost half, 13 million tonnes dm, is available in the state of Uttar Pradesh (see Kumar et al., 2017; Jain et al., 2014). Earlier, most of the trash was being burned in the field due to its bulky nature and high cost incurred in collection and transportation. However, now farmers bale the trash with a baling machine for easy handling, transport and storage and use it for crop mulching. Mulching with trash helps in reducing evapotranspiration loss and the crop is saved from high temperature. Very few farmers (approx. 10%) burn the trash.	Medium (20%-40% of technical potential)
Sugarcane	Trash	Thailand	Cane residues (mainly tops and leaves) are left in the field. These residues serve as soil enrichments thus improving the physical, chemical and biological properties of soil.	
Sugarcane	Trash	Pakistan	Agricultural Mechanization Research Institute (AMRI) Wing, Faisalabad has designed and developed a sugarcane stripper. Sugar cane stripper can be used to remove trash from the sugarcane stalks, which can be used as one of the available biomass resources for energy production.	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Sugarcane	Bagasse	India	Bagasse is used as a fuel for sugar mill boilers and in case if surplus is available, tendering process is followed and buyer collects the bagasse at their own cost.	
Sugarcane	Bagasse	Thailand	Traditionally, rice residue is either burnt or incorporated into the fields for the next crop (Phongpan and Mosier 2003). Residues of rice and sugarcane consist of approximately 83% of the total burnt residue in Thailand (Kumar et al. 2020). Rice residue burnt annually is about 4.8 million tonnes (70% of the total) followed by sugarcane at an average of 1.1 million tonnes (13% of the total). Central and Northeastern regions have the highest contribution to burnt rice residue, whereas the North has the highest percentage of burnt sugarcane residue. The Electricity Generating Authority of Thailand has adopted the small power producers (SPP) program which is a multinational program that accounts for about 15% of the country's total installed generating capacity and fuel from biomass is used in many of these SPPs. Out of these SPPs (10-90 MW), 16 use paddy husk as fuel at an installed capacity of 140 MW, straw however has not been used due to limitations in logistics. The Thailand government implemented the Alternative Energy Development Plan (AEDP) in 2012, in which they hope to achieve about 5570 MW of power from biomass by 2036. Current usage of residue for biofuel is only at 42% of the total potential, and paddy straw and sugarcane top and trasher is yet to be used, however, a small percentage of sugarcane bagasse is being used (Kumar et al. 2020). In 2016, sugar factories in Thailand left bagasse around 30.68 million tons which were used to generate 3885.34 million kWh electricity. (Chunhawong et al. 2018)	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Sugarcane	Bagasse	Pakistan	According to a research, 17,900,000 tonne of bagasse were produced from 8 sugar mills during 2009 in Pakistan. It was estimated that around 1,400 MWh electricity could be produced from such an amount of bagasse (Khan, 2010). Ramzan Sugar Mills Limited (RSML) is a 12,000 TCD sugar plant operating for about 120 days in a year. The factory has a capacity of about 500 TCH. Considering the utilization factor at 90%, the total cane crushed for 120 days turns out to be 1296000 tonnes. The bagasse generation in the plant is 30% on cane Once fine bagasse is used for enhancing filtration in the sugar process, a bagasse quantity of 29% on the cane crushed is available for use in the boilers. So, the total bagasse production is 375840 Tons which is currently being used to generate 60 MW of electricity for 150 days including a crushing period of 120 days.	
Rice	Straw	Bangladesh	According to 'Methanogenic populations involved in the degradation of rice straw in anoxic paddy soil', the direct incorporation of rice straw in the soil can have a bad impact on the next crop and also may cause increasing CH4 emissions from the fields (Weber et al., 2001). Since, rice straw has large potential for plant nutrients in organic farming, therefore, composting of agricultural waste is a sustainable solution to the common problem of organic wastes disposal (Mastouri et al., 2005). According to a study by Bangladesh Institute of Nuclear Agriculture, rice straw can also be used in strawberry production through composting to increase the yield and sweetness of strawberry.	
Rice	Straw	Cambodia	Rice straw is used as fertilizer for the next crop to be sown in many cases. This is common in the provinces around the Tonle Sap lake. Bales of straw are also used for cattle fodder. Rice bran is also used for this. Local rice millers are known to use rice husk for biofuel purposes.	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Rice	Straw	India (Punjab, Uttar Pradesh and West Bengal)	Samaddar et al. (2017) did a detailed review of uses of rice straw in India and showed very different use levels per region. In the main rice production regions the following was observed: Punjab: The majority of the straw (70%–80%) is burned in the field, 7% is used for livestock feed, and 1%–2% is used for roof construction. It is estimated that Punjab produces around 180-200 lac tonnes of paddy stubble every year. Experts and practitioners working in the management of paddy straw indicate that the combined efforts to manage paddy straw leads to only 40-45% of lifting and management leaving the remaining 60% straw to be burnt. Farmers say they have no option but to burn the straw as the time limit for them to prepare for the field for the sowing of wheat is too small. Farmers are willing to give their straw but their only concern is that whosoever is interested in taking the waste material should collect the entire volume and there should be no delay in picking the stubble. While the farmers agree that their current practice of burning the stubble is not an effective one and leads to environmental pollution and impacts human health, they put the onus on the government to create large scale and time efficient solutions for the effective disposal and management of paddy straw. Current efforts in managing paddy straw are limited to conversion of agri-waste to energy and some efforts in making packaging products like cardboard boxes. The natural solution for the management of straw is the crushing the stubble in the field which acts as a manure does not elucidate a lot of interest from the farmers. The government called for harvesting the paddy field using a combined harvester fitted with Super-Straw Management System equipment, which chops and evenly spreads the stubble in the field.	in Punjab: High (60%-80% unused) In Uttar Pradesh: Medium (20%-40% unused) West Bangal: Low (<20% unused)
Rice	Straw	India (Punjab, Uttar Pradesh and West Bengal)	Happy Seeder (HS) or Turbo Happy Seeder (THS), a tractor-operated machine developed by the Punjab Agricultural University (PAU) in collaboration with Australian Centre for International Agricultural Research (ACIAR), for in-situ management of paddy stubble (straw) was recommended to farmers in 2005-06. The cost of the Happy Seeder is around Rs 1.50 to 1.60 lac. The agriculture department gives 80 per cent subsidy to farmer groups and 50 per cent subsidy to individual farmers. From the limited interaction with farmers and farmer cooperatives, the willingness to manage paddy straw using farm mechanisation is very low. According to newspaper reports, Punjab produced around two crore tonnes of paddy residue last year, of which 98 lakh MT were burnt last year. Similarly, in Haryana, farmers burnt 12.3 lac tonnes of the 70 lac tonnes of paddy residue produced. Uttar Pradesh: Around 30% of the straw is used as fodder for livestock, 22% is burned in situ, 19% is incorporated in soil, and 16% is sold in the market. Rice straw is considered as the most important dry fodder for livestock feed, while 60%–70% is used for this purpose and 10%–15% is used as household fuel. The rest of the rice straw is used for roof making and packaging. According to the Ministry of Finance, Government of Bangladesh, straw based feed is the main feed in the aspects of Bangladesh which constitutes about 87% of the total dry roughage and 72% of total roughage	in Punjab: High (60%-80% unused) In Uttar Pradesh: Medium (20%-40% unused) West Bangal: Low (<20% unused)
Rice	Straw	Indonesia	Since, rice straw is abundantly available from cultivating rice, farmers offer rice straw as the main roughage source to their animals. This is particularly the case in Southeast Asian countries such as Thailand, Vietnam and Indonesia (NARC newsletter, 2004)	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Rice	Straw	Pakistan	For every 4 tons of rice or wheat grain, about 6 MT of straw is produced. Around 43,437,000 tonnes of RWS is produced in Pakistan (Bhutto et al, 2010). In Pakistan wheat and rice straw form the basis of animal feed resources and are used in high rates. Straw is also used in paper and packaging material, mat, wall construction etc.	
Rice	Straw	Sri Lanka	In the dry zone areas some of the straw is used for biofuel purposes. Paddy husk is used as an input in cement factories and is often transported large distances to be used in these factories. Compared to straw, paddy husk has a more concrete presence in Sri Lanka, especially in the biofuel sector. Incorporation into the soil is common where mechanized harvesting is implemented. Half-burnt husk is incorporated into the soil in wet-zone regions. Straw is also used as fertilizer in many cases.	
Rice	Straw	Thailand	Traditionally, rice residue is either burnt or incorporated into the fields for the next crop (Phongpan and Mosier 2003). Residues of rice and sugarcane consist of approximately 83% of the total burnt residue in Thailand (Kumar et al. 2020). Rice residue burnt annually is about 4.8 million tonnes (70% of the total) followed by sugarcane at an average of 1.1 million tonnes (13% of the total). Central and North-eastern regions have the highest contribution to burnt rice residue, whereas the North has the highest percentage of burnt sugarcane residue. The Electricity Generating Authority of Thailand has adopted the small power producers (SPP) program which is a multinational program that accounts for about 15% of the country's total installed generating capacity and fuel from biomass is used in many of these SPPs. Out of these SPPs (10–90 MW), 16 use paddy husk as fuel at an installed capacity of 140 MW, straw however has not been used due to limitations in logistics. The Thailand government implemented the Alternative Energy Development Plan (AEDP) in 2012, in which they hope to achieve about 5570 MW of power from biomass by 2036. Current usage of residue for biofuel is only at 42% of the total potential, and paddy straw and sugarcane top and trasher is yet to be used, however, a small percentage of sugarcane bagasse is being used (Kumar et al. 2020).	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Rice	Straw	Vietnam	An experiment carried out on buffaloes by Cantho University, Haugiang, Vietnam, (Nguyen Van Thu et al 1994a) indicated that giving molasses-urea cake to native buffaloes in the Mekong river delta fed on rice stubble and straw improved health and productivity. The study further concluded that supplement cakes containing urea, molasses, rice bran, coconut oil meal, salt, bone meal and trace elements supported good health and working capacity of native cattle and buffaloes in areas where feed and water shortages occurred. In addition, Thu et al (1996), reporting several on-station and on-farm experiments, showed that 4% urea treated rice straw either fed alone or together with urea-molasses cake resulted in increased nitrogen content of straw, feed intake, health status, draught power and milk yield of working and dairy buffalo compared with those of buffalo fed on untreated straw as controls (FAO, 1998). Vietnam has about 44.0 million tonnes of dry rice straw per annum. Hung et al. (2016) reported about 90% of rice production area is harvested by combine harvesters which only cut 1/3 the upper top of the rice tree. This part of rice straw is collectable and can be used as ruminant feed. Therefore, rice production annually generates approximately 13.0 million tonnes of dry collectable rice straw. This is an abundant and sustainable feed source for ruminant feed. Rice straw can be used directly or treated by different preserved methods to store and improve nutritive value of the rice straw for animal feed during forage-shortage period. Rice-straw bioethanol production could reduce annual gasoline consumption by >20%, and plant construction costs accounted for 8–22% of the total investment (Yoji & Tatsuki, 2013).	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Wheat	Straw	India (Punjab)	In Punjab, the main wheat production area, Jair (2014) reports that between 10%-23% of the straw is burned in the field. The remaining straw is used for feed and other uses. It is believed that almost 40 % of the wheat straw produced in the state of Punjab is used as dry fodder for animals. However, to encourage the use of rice residue as fodder for animals, a pilot project was taken up by PSCST at PAU under which trials on natural fermentation of paddy straw for use as protein enriched livestock feed were conducted. The cattle fed with this feed showed improvement in health and milk production. The technology was demonstrated in district Gurdaspur, Ludhiana, Hoshiarpur and Bathinda. The department of Animal Husbandry, Punjab has propagated the technology in the state (Anoop & Ritesh, 2018)	Low (<20% unused)
Wheat	Straw	Pakistan	Wheat is harvested on a massive scale every year and the residues are helpful in maintaining the soil fertility if added as such or by mixing with the urea to balance the nitrogen content in the field (Murray and Bruehl, 1983). Extracellular hydrolytic enzymes are being produced using wheat straw under submerged Fermentation (SF) as well as Solid-State Fermentation (SSF) systems. A large number of secondary metabolites can also be obtained by fermentation of Wheat Straw (Yasin et al., 2010). Non-wood fibres containing cellulose and hemicellulose have a long history as a raw material in study and pulp industry (Singh et al., 2009). Wheat straw can be easily pulped and bleached with about 40% yield and it produces fine textured study (Mubeen & Khan., 2012). Wheat straws are traded within and among the districts of Sindh each year in bulk. Large traders buy wheat straw from rural areas and sell where they find profit. Some of them store the straw for longer periods to maximise the profit and some do pressing as well.	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Wheat	Straw	Pakistan	There are three types of wheat straw consumers: (1) Dairy farms; (2) Landless livestock rearers who own a small number of animals for household use; and (3) Better off livestock owners who grow straw but are only able to meet about 50% of their need. Dairy farms often buy a large amount from traders and stockists and store it within the farm's courtyard, while landless livestock rearers buy from retailers. (Matthews & Hussain, 2015)	
Sorghum	Stalks/ straw	India	Sorghum residue and grain is mainly used in animal feed, alcohol distilleries and starch industries in India (Kleigh et al. 2018).	
Oil Palm	Empty Fruit Bunch	Indonesia	The availability of Oil Palm Empty Fruit Bunches (OPEFB) will continue to increase along with the increase in the production of fresh fruit bunches of palm oil in Indonesia. OPEFB has enormous potential to be developed into high value-added products. Chemically the OPEFB contains lignin> 20%, hemicellulose> 25% and lignocellulose> 35%. All three components can be converted into various chemicals, materials and valuable products. Utilisation of soil improver and co-composting has been widely applied in Indonesia. However, due to the environmental pollution, the incineration of OPEFB has been avoided. In order to protect the environment and to ensure the sustainability of the oil palm industry, the OPEFB must be fully converted. The building block of native OPEFB fibre is made up from a complex matrix of three main polymers which are cellulose, hemicellulose and lignocellulosic. The lignocellulosic material from OPEFB has been considered as a very good source of fermentable sugar for conversion into value added products (Rame, 2018). OPEFB were extensively largely dumped and traditionally been burnt in the incinerator of the palm oil mill and ash recycled into the plantation as fertilizer. Utilization of soil improver and co-composting has been widely applied in Indonesia.	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Oil Palm	Empty Fruit Bunch	Thailand	Thailand has an interest in the use of alternative energy sources more. Thailand has conducted research to support the EFB to bring it back to beneficial use. In the south of the country is used it as fuel to generate electricity	
Maize	Stover/ straw	India	A significant majority of maize residue is used as cattle fodder (Bimbraw 2019). Other uses include but are not limited to soil mulching, bio-manure, thatching for huts and fuel for domestic and industrial use (Devi et al. 2017).	
Maize	Stover/ straw	Indonesia	Maize stover (or straw) normally consists of variable proportions of the leaves, stalks, and cobs of maize plants left in a field after harvest. It can be a valuable addition in ruminant feeding systems (dairy, beef, heifers, as well as sheep and goats) as it has the highest feeding value of all cereal straws. It is also a good source of fibre, which can replace cereal straws if they are not available, if additional fibre is needed or if there is a lack of forage.	
Banana & plantain	Pseudo-stem	India	Banana leaves are used as a fodder and mulching purpose. Some of the residues are processed to be used in construction applications. Banana peels and sugarcane waste are being utilized in the paper industry.	
Banana & plantain	Pseudo-stem/ trunk	India	In Jalgaon district of Maharashtra state, bulk of banana pseudo-stem is used to prepare a plant growth regulator. There is no transportation required from the farmer's end as the manufacturer collects the biomass directly from the farmer's field. Few farmers with the help of rotavator bury the pseudo stem residues in the field only which afterwards decomposes and improves soil organic matter. In case of surplus biomass availability, farmers use decomposing culture to convert the residues in compost	
Coconut	Husk	India	Coconut husk has many uses in India. A spongy material that binds the coconut fibre in the husk known as Coir Pith husk fibre, is used as a raw material for carpets, stuffing seats and cushions, fertilizers in agriculture etc., (Samant and Gaikwad 2020). The fibrous husk is also used to brush teeth in South India for its benefits in dental care. Coconut coir fibre is used to make ropes, binderless board production, as shell for buttons, as charcoal and in decorative carving. Activated carbon derived from the coconut husk is characterized by a high percentage of micropores that help in removing odorous and volatile organic compounds. Coconut husk can also be used in the building of cost-effective building material and roofing for houses (Srivastava and Kumar 2018).	
Coconut	Husk	Indonesia	Coconut husk is a coarse fibre extracted from the fibrous outer shell of a coconut. Studies have shown the possibility of preparing particle boards using coconut husk and its by-products, which confirms to the specification of wood. Coconut husk is one of the important by-products of coconut tree and coconut-based activities. Husks are the outer fibre (35%) of the nut, followed by the hard protective shell (12%). Coir wood is the material for a sustainable future made from the husk of the coconut. Husks are a useful source of potash and valuable mulch for the conservation of moisture. Husks are often burned to produce ash, which is used to fertilize the trees. Burying the husk in the soil is more beneficial than burning. These husks are used as mulch for the conservation of moisture in the soil. A layer of husk is placed in a ring, convex side upwards from about 0.3 m up to a distance of 1.8- 2.1 m from the base of the palm. This method is beneficial during periods of drought. Husks can also be used in planting holes during coconut seedling transplantation (Annamalai et al, 2017).	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Pineapple	Leaves	India	In India, Pineapple leaves are mostly just either burnt or incorporated into the soil (Hazarika et al. 2017). The pineapple leaves can be used to extract bromelain (an enzyme mixture present in the pineapple) at local level (Nair Anand 2019) and is also used by a few of the industries in the manufacture of medicines and cosmetics, due to other useful compounds such as citric acid and anti-inflammatory properties. Leaves may also be used to produce products like fabrics, papers, bags and ropes. It can also be used as a low-cost feedstock for bioethanol production using 2% dry yeast (Casabar, Unpaprom, and Ramar).	
Pineapple	Leaves	Indonesia	Density of PALF is similar to other natural fibres while Young's modulus is very high, and tensile strength is highest among the related natural fibres. These properties are suitable for its application as building and construction materials, automotive components, and furniture.	
Pineapple	Leaves	Thailand	According to a journal based on 'Pulp and Paper Production from Pineapple Leaves', only 52 % of pineapple fruit is used for jam and juice production and the remaining 48% consists of fruit peel and leaves forming the waste. The pineapple wastes are rich in lignin and cellulose and form a very good raw material for allied fibres. According to several studies, the textile made from pineapple leaf fibres can be used as an alternative to leather. The discovery was made by a Spanish designer, Carmen Hijosa, who was in the business of designing and manufacturing leather goods in Ireland. PALF can be produced using better processing and made accessible to discerning customers. The silky white fibre can easily be dyed and made into a firm fabric that's softer than hemp, resembling linen (Yogesh and Hari, 2015). PALF blends well with other materials such as Recycled Polyester, Organic Cotton and Lyocell/Tencel to form yarn of different sizes, single or multi-ply. The result: comfortable, eco-friendly apparel, footwear and interiors.	

Crop	Residue	Country	Known competing uses	Likeliness of unused potential
Pineapple	Leaves	Thailand	Due to a large amount of leftover every day, the idea of converting these fibres into handmade paper which can increase their commercial value as well as create jobs for villagers was conceived. One sheet of finished pineapple fibre paper can sell much higher than the price of raw fibres sold as animal feed (Yusof et al, 2012).	
Pineapple	Leaves	Vietnam	Extracted fibres from pineapple leaves being utilized for developing successfully eco-friendly and cost-effective pineapple fibres (PFs) aerogels by using polyvinyl alcohol as a cross-linker and following a freeze-drying method. (Luu et al, 2020).	
Okra	Leaves/ stems	India	Okra leaves are used in Indian cuisine in many cases due to its vitamin A & C content, calcium, protein and iron (Grant 2019).	
Okra	Leaves/ stems	Pakistan	**Okra foliage can be used for biomass. The stem of the okra plant provides fibre which is used in the paper making industry (Ford-Lloyd and Armstrong, 1993).**	

Annexure 4
Identification of hub locations and spatial mapping

Description of hub locations identification

Given the three different capacity levels for cellulose extraction mills, the starting points for the identification of different hubs in the region per type of biomass are presented in Table A4.1. For fibres the minimal demand for biomass is based on a fibre amount ranging from between 100 to 1000 tons fibres a year. A real minimum demand is not set. Except that the hub locations selected for these fibre chains are placed where there is the largest and most concentrated availability in the eight focus countries.

Table A4.1: *Biomass types and assumptions to identify hub locations in the spatial assessment*

Crop	Residue	Type of residue Field or mill	For cellulose or fibre?	RPR to technical potential in ton dm	% cellulose in residue	% fibre in residue	Min. cellulose or fibre production Year in hub [kton dm/year]
Sugarcane	Trash	Field	Cellulose	0.3	0.34	n.a.	75
Sugarcane	Bagasse	Sugar mill	Cellulose	0.14	0.46	n.a.	75
Sugarcane	Bagasse	Sugar mill	Cellulose	0.14	0.46	n.a.	150
Sugarcane	Bagasse	Sugar mill	Cellulose	0.14	0.46	n.a.	500
Sugarcane	Bagasse & trash	Combination	Cellulose	0.14	See above	n.a.	150
Sugarcane	Bagasse & trash	Combination	Cellulose	0.14	See above	n.a.	500
Rice	Straw	Field	Cellulose	1	0.38	n.a.	75
Rice	Straw	Field	Cellulose	1	0.38	n.a.	150
Rice	Straw	Field	Cellulose	1	0.38	n.a.	500
Rice & Wheat	Straw	Field	Cellulose	0.85	0.4	n.a.	500
Oil Palm	EFB	Oil palm mill	Cellulose	0.19	0.41	n.a.	75
Oil Palm	EFB	Oil palm mill	Cellulose	0.19	0.41	n.a.	150
Banana & plantain	Pseudo-stem	Field	Fibre	0.15	n.a.	2%	0.1-1
Pineapple	Leaves	Field	Fibre	0.25	n.a.	10%	0.1-1

Table A4.2: *Best hub locations identified for rice straw sourcing for cellulose extraction*

HS code	Country	Region	Size of cellulose extraction plant (Kton cellulose/year)	Sourcing feedstock
9	Bangladesh	Rajshahi	Medium & -Large (250/500 Kton/yr)	Rice straw
5	Cambodia	Takêv	Small/Medium (75/150 Kton/yr)	Rice straw
3	India	Andhra Prades	Medium/large (150/500 Kton/yr)	Rice straw
8	India	Punjab	Medium/large (150/500 Kton/yr)	Rice straw & wheat straw
10	India	West Bengal	Medium/large (150/500 Kton/yr)	Rice straw
7	Indonesia	Jawa Timur	Medium/large (150/500 Kton/yr)	Rice straw
13	Indonesia	Jawa Tengah	Medium/large (150/500 Kton/yr)	Rice straw
2	Pakistan	Sind	Small/Medium (75/150 Kton/yr)	Rice straw
6	Sri Lanka	Polonnaruwa	Small/Medium (75/150 Kton/yr)	Rice straw
4	Thailand	Suphan Buri	Medium/large (150/500 Kton/yr)	Rice straw
11	Vietnam	Thái Bình	Medium/large (150/500 Kton/yr)	Rice straw
12	Vietnam	An Giang	Medium/large (150/500 Kton/yr)	Rice straw

Table A4.3: *Best of hub locations identified for sugarcane trash and bagasse sourcing for cellulose extraction*

ID	Country	Region	Size of cellulose extraction plant (Kton cellulose/year)	Sourcing feedstock
16	India	Uttar Pradesh	Medium/large (150/500 Kton/yr)	Bagasse & trash
17	Pakistan	Punjab	Small/Medium (75/150 Kton/yr)	Trash
19	Thailand	Uthai Thani	Small/Medium (75/150 Kton/yr)	Trash
20	Indonesia	Lampung	Small/Medium (75/150 Kton/yr)	Trash

Table A4.4: *Best hub locations identified for biomass sourcing for fibre extraction*

ID	Country	Region	Size of cellulose extraction plant (Kton cellulose/year)	Sourcing feedstock
0	Bangladesh	Khulna	100-1000 ton/year	Banana pseudo-stem
1	India	Maharashtra	100-1000 ton/year	Banana pseudo-stem
2	Thailand	Samut Prakan	100-1000 ton/year	Banana pseudo-stem
3	Vietnam	Kiên Giang	100-1000 ton/year	Banana pseudo-stem
4	Indonesia	Jawa Barat	100-1000 ton/year	Banana pseudo-stem
14	Thailand	Kamphaeng Phet	100-1000 ton/year	Pineapple

Explanation for spatial mapping using MAPSPAM

There were no spatial data on crop area land use until recently, therefore a collaboration was started in 2002 between FAO, IFPRI (International Food Policy Research Institute) and SAGE (Center for Sustainability and the Global Environment, University of Wisconsin-Madison) titled 'Agro-MAPS' (Mapping of Agricultural Production Systems). Firstly, a large database on Agro-Maps was compiled, which was filled by crop area and production data collected in a large network of organisations from various local subnational offices in many countries throughout the world. Currently, most of the data used are from World Food Programme (WFP) crop and food supply assessment mission surveys, agricultural performance surveys, national bureaus of statistics, regional agricultural centers, ministries of agriculture, rural and extension services, regional NGOs, household services, ministries of the environment, and water resource groups. This resulted in a robust database with crop production data for more crops, and smaller administrative units than any single global collection of subnational production data currently available. These data were compiled from a variety of formats into standard spreadsheets and database files (the 2010 data were used in this study).

In total, 42 different crops were included in the SPAM 2005 and 2010 databases. Their definition follows FAO terminology (especially crop nes = crop not elsewhere specified). For this project crop data layers were used for all the crops that produce the selected residues as presented in Table 3.3.

Estimation of crop distribution within a statistical unit is done in SPAM for the physical area. However, statistical information refers in general to harvested areas, from where crops are gathered. SPAM considers 42 crops and handles each crop as if it was grown by itself on a plot, which often is not the case. In many countries, there are regions and seasons where more than one crop is grown simultaneously on one plot. Frequently there is a succession of different crops on one plot throughout the year, especially in tropical countries. All these facts are combined in a cropping intensity parameter for each crop, which is larger than 1 when there is multi-cropping, or more than one harvest per year from one plot, of different crops.

For the allocation of the crop in SPAM to the physical area crop-specific suitability information is taken into account, such as climate and soil conditions. Different crops have different thermal, moisture, and soil requirements, particularly under rainfed conditions. FAO, in collaboration with the International Institute for Applied Systems Analysis (IIASA), has developed the agro-ecological zones (AEZ) methodology based on an evaluation of existing land resources and biophysical limitations and potentials for specific crops (FAO/IIASA). This methodology provides maximum potential and biophysically attainable crop yields and suitable crop areas. For SPAM three production system types from the FAO/IIASA suitability datasets: Irrigated high-high input; rainfed – high input/commercial; rainfed – low input/subsistence were utilised. The latter type is also used for rainfed – subsistence farming when attainable yields are needed. For each crop and in each production system, the suitable land is defined as the sum of the four suitability classes in the AEZ model: very suitable, suitable, moderately suitable, and marginally suitable.

For the cropland extent to which the crop data are allocated satellite-based land cover datasets were used.

There are several global and regional land cover datasets publicly available for various years: GlobCover 2005, MODIS v.5, AFRICOVER, GLC-2000, ISCGM, CORINE, and a number of national maps. Each dataset has its own pros and cons depending on the region of the world. Following the methodology described in Fritz et al: "Mapping Global Cropland and Field Size", IIASA/IFPRI, 2015. all data sets were combined resulting in a global cropland map at a resolution of 30 arc seconds (approx. 1x1km at the equator) and aggregated to a five-minute (approximately 10x10km2 at the equator and mostly 9*9 km2 in most of the 8 focus countries of this study) resolution for input to the SPAM allocation.

The final spatial allocation in SPAM is subject to constraints (limits) dictated by existing:

- agricultural area
- irrigated area
- suitable area (suitability per crop)
- crop area statistics (totals per administrative region)

According to these constraints the optimal allocation is solved in an optimization model written in GAMS. For further details see You (2014 and 2020).

The data that was used from MAPSPAM in this study refer to statistical data from the year 2010. For the spatial distribution data for okra and pineapple, the data from the year 2000 were used. The spatial data from MAPSPAM was compared with more recent statistical data (for 2018-2020 years) and in some regions small crop area changes were seen, but since these are in the error range they had minimal effect on the final cost assessment results than the more general conversion factors for RPR (residue to product ratio) and average cellulose and fibre contents used to calculate the residual biomass total and cellulose and fibre potentials per location.

Annexure 5

Detailed description of chain design and cost assumptions for delivery of selected residual biomass at plant gate

For the purchase cost
A review of prices paid for fibres by Dunne et al. (2016) showed that prices paid for extracted fibres from bananas were between 0.1-0.8 USD/kg. For fibres from pineapple leaves this level was 0.05 USD/kg. The study assumes that a purchase cost level of 0.05 USD/kg of fibre contained in the biomass is a reasonable level to make initial cost calculations with. See Table A5.1 for how this assumption works out per fibre source.

For the purchase level cost for the residues used for the cellulose extraction process assumed for the selected residual feedstocks are presented in Table A5.2. These are based on a very rough estimation of the average market price of the residue.

For the compensation cost for fertiliser removal, these costs were allocated only to the field residues used for cellulose extraction. This is because it will be very challenging to bring any residues back to the field after extraction of the cellulose. For fibres this would be possible, so the return transport cost is allocated.

The cost of the fertiliser compensation for residues for cellulose extraction were calculated taking the content of the NPK minerals contained in the field residues (based on FAO, 2005, for rice and cereal straw in India and on Suma et al. (2015) for sugar-cane trash). The cost of fertilisers was ascertained from FAO (2005) and cost levels were extrapolated from 2005 to 2020 using an inflation correction rate. Differences in price levels between countries were calculated based on fossil fuel price levels. The results of this approach are presented in Table A5.3.

For up and off-loading cost when the biomass is transported, it is assumed that this would cost 0.50 USD/tonne for every up and offloading combination in the chain. In chains, for treatment in an ICP, the up and off-loading will double vis-à-vis the chains that assume transport of biomass directly from the field or mill to the cellulose of fibre extraction mill.

Densification cost: Densification of residues to form pellets is a key intermediate process carried out at the ICP plant. These densification costs prior to long-distance transport are estimated on the basis

Table A5.1: *Purchase cost level for residual biomass for fibre extraction*

	Fibre contents in dm residue	Cost per ton biomass dm (USD)	Cost per ton biomass wet (USD)	Cost per ton biomass wet (USD)
Banana pseudo-stem	2%	1	0.15 or 0.45*	0.45
Pineapple leaves	10%	2	0.5	
Okra stem	12%	2.4	0.672	

* 0.15 USD is for a whole pseudo-stem and 0.45 is for the prepared out pseudo-stem which has the same amount of fibre, but concentrated in 30% of the biomass of the pseudo-stem.

Table A5.2: *Purchase cost level for residual biomass for cellulose extraction*

	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam
Purchase price Rice straw (USD/tonne 14% moisture)*	24	24	24	24	24	24	24	30**
Purchase price Wheat straw (USD/tonne 14% moisture)			40					
Purchase price Sugarcane trash (USD/tonne 14% moisture)			20	20	20		20	
Purchase price Sugarcane bagasse (USD/tonne 40% moisture but high cellulose content then trash)			20	20	20		20	
Purchase price EFB of palm oil mill (USD/tonne 50% moisture)				10			10	

* According to Elbersen & Keijser (2019) ' Farmer gets €21 per ton rice straw' in Haryana region. In other Indian regions competing use levels can be higher, so an average cost level of 24 US$/ton

** Many increasing competing uses (see: https://www.phnompenhpost.com/business/mekong-delta-rice-farmers-earn-big-selling-straw)

Table A5.3: *Purchase cost level for residual biomass for cellulose extraction*

	Bangladesh	Cambodia	India	Indonesia	Pakistan	Sri Lanka	Thailand	Vietnam
Rice straw (USD/tonne)	4.8	5.9	5.6	3.6	5.5	5.2	4.4	4.6
Sugarcane trash (USD/tonne)			4.8	3.1	4.1		3.8	

Sources: **On mineral content and price of fertilisers**:
- FAO (2005). Fertilizer use by crop. FAO Land and Plant Nutrition Management Service Land and Water Development Division in India. First version, published by FAO, Rome, 2005.
- Suma R, Savitha CM (2015) Integrated Sugarcane Trash Management: A Novel Technology for Sustaining Soil Health and Sugarcane Yield. Adv Crop Sci Tech 3: 160. doi:10.4172/2329-8863.1000160

Fossil fuel price levels per country: https://www.theglobaleconomy.com/rankings/diesel_prices/ and https://nl.globalpetrolprices.com/diesel_prices/

of a previous study covering the pelletising costs for straw and miscanthus in Ireland (Nolan et al. 2010). The table below translates the pelletising costs (capital and operating) from Ireland to India. This analysis, and further extension from India to the other seven countries, accounts for differences in fuel and labour costs in each country.

Storage cost in case biomass is not available whole year round because of seasonality and need to keep cellulose dissolving mill operational through the year. Storage costs were based on the BECOOL project review on storage cost. The average cost of storage covered is about 1.1 USD per m3 per month.

Transport which can be local and short and long distance

For short distance transport and for all non-densified residues that are transported directly from the field to the cellulose and fibre extraction plant it was assumed that they use small trucks with 70 to 140 kg capacity to bring the residues further. Cost assumed for local transport = 0.20 US$ per ton/km.

For long term transport of densified biomass or of biomass that can be picked up from sugar or oil palm mills the cost of freight movement by road information was used from the Indian National Transport Development Policy Committee.[1] They published that road transport costs are INR 2.58/tonne/km (=0.034 USD/tonne/km) as compared to INR 1.41/ton/km for rail and INR 1.06/tonne/km for waterways. Since the cost level is for 2014 a conversion rate in 2014 was 60 INR to 1 USD. Transport cost was: 0.043 USD/tonne/km. To compensate for inflation, 0.050 USD/ton/km. was used. From the Indian cost levels, it was derived that extrapolated the cost level to the other seven focus countries by applying the index for differences in fossil fuel prices.

Detailed cost calculation results for cellulose sourcing from rice straw

For delivering rice straw to the cellulose dissolving plant, two chains are considered. The first involves the densification of the straw to pellets in intermediate collection point which makes long distance transport cheaper. The second chain excludes this densification,

	Ireland (2010)		Ireland (2020) @14.25% inflation for 2010-20*		India (2020)	
(all costs in USD/tonne)	Capital cost	Operating cost	Capital cost	Operating cost	Capital cost	Operating cost
Straw grinding plant	1.78	8.11	2.03	9.27	2.03	5.2
Pelleting cooling plant	2.47	9.04	2.82	10.33	2.82	5.8
Misc. electric equipment	0.66	0	0.75	0.00	0.75	0.0
Compressed air plant	0.02	0.16	0.02	0.18	0.02	0.1
Storage bin	0.06	0.01	0.07	0.01	0.07	0.0
Industrial loader & fork lift	0.33	0.21	0.38	0.24	0.38	0.1
Office, building, land use	1.31	0.47	1.50	0.54	0.15	0.3
Labour		9.31	0.00	10.64		1.1
TOTAL	6.6	27.3	7.6	31.2	6.2	12.5

* Source for inflation rate: https://www.inflationtool.com/euro/2010-to-present-value Nolan (2010)

1 National Transport Development Policy Committee. India Transport Report—Moving India to 2032. 2014. Cited by NITI Aayog. 2018. EFFICIENCY AND SUSTAINABILITY IN INDIAN LOGISTICS.

but assumes direct transport of the straw bales from the field to the cellulose dissolving plant.

The results of the cost calculations for cellulose capacities of 75, 150 and 500 kilotons cellulose production per year are presented in Table A5.4 assuming a 30% contractibility level for rice straw per hub. In the first 6 columns, all costs are included, while in the last six columns of the purchase costs are assumed to be zero. Presenting cost with and without purchase cost is done because there is large uncertainty about these costs which can vary strongly per region and per year. Presenting the total cost excluding the purchase cost will also provide a better understanding of the process of transport cost changes with increasing collection distances and spatial biomass dispersion.

From Figure A5.1 and Table A5.4, it becomes clear that densification in an intermediate collection point is relatively expensive and increases the delivery cost of biomass significantly. The effect of densification on cost reduction in transport is not enough to compensate for the high pelletising cost. It seems that in hub locations direct transport of bales from the field to the cellulose dissolving plant is cheaper. This is also shown in the Figure A5.1 in which the relation between total delivery cost and distance to hub location for Andhra Pradesh is presented.

If the purchase costs are not considered, it can be concluded that the lowest at-gate cost for rice straw delivery at the dissolving plant gate is found in the two hub locations in Indonesia where bales can be delivered to a medium and large dissolving plant at 28 and 35 USD/ton cellulose, respectively.

The highest cost for such situation is found in Pakistan for the medium size cellulose dissolving plant and in Andhra Pradesh in India for the large cellulose plant. On average over the 12 hub locations the delivery cost of rice straw pellets amounts to 37, 37 and 43 USD/ton cellulose for a small, medium and large size dissolving plant respectively. If the purchase cost assumed in the study are included in the total cost this average becomes 100, 114 and 123 USD/ton cellulose, respectively.

In case of pellets, if the purchase cost is not included, the lowest delivery cost for a medium size dissolving plant is found in Indonesia in Jawa Timur amounting to 65 USD/ton cellulose. Looking at the large cellulose dissolving plant, the lowest delivery cost for bales are also found in the same location at almost the same costs. On average for all hub locations these delivery costs amount to 75, 81 and 83 USD/ton cellulose to a small, medium and large size dissolving plant respectively. The cost of delivery of pellets is around twice that of bales.

Figure A5.1: *Relationship between total delivery cost and distance to dissolving plant location at different sourcing capacities for Andhra Pradesh in India*

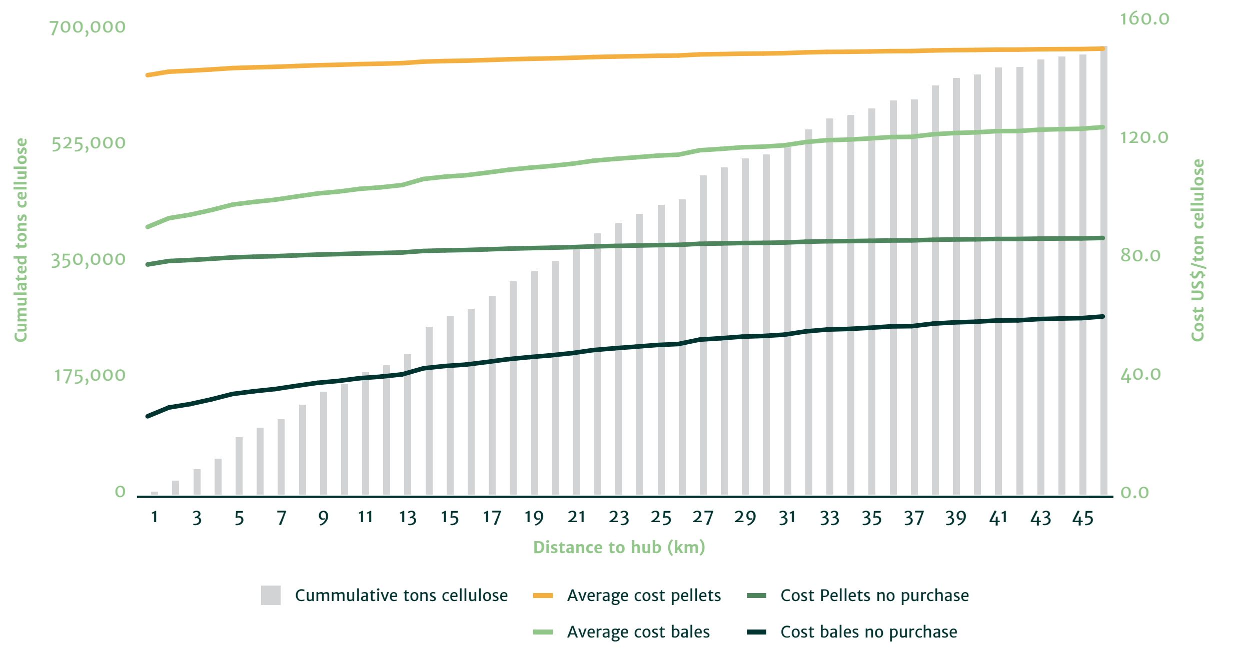


Table A5.4: *Overview of rice straw delivery cost in USD/tonne of cellulose for different chains*

			Pellet cost_including purchase cost (USD/ton cellulose)			Bales cost_including purchase cost (USD/ton cellulose)			Pellet cost_NO purchase cost (USD/ton cellulose)			Bales cost_NO purchase cost (USD/ton cellulose)		
HS	Country	Region	75 Kton	150 Kton	500 Kton	75 Kton	150 Kton	500 Kton	75 Kton	150 Kton	500 Kton	75 Kton	150 Kton	500 Kton
9	**Bangladesh**	Rajshahi	n.a.	138	139	n.a.	98	102	n.a.	75	76	n.a.	34	39
5	**Cambodia**	Takêv	n.a.	147	149	n.a.	102	110	n.a.	84	85	n.a.	39	47
3	**India**	Andhra Pradesh	n.a.	144	148	n.a.	101	117	n.a.	81	85	n.a.	38	54
8	**India**	Punjab	n.a.	144	146	n.a.	102	109	n.a.	81	83	n.a.	39	46
10	**India**	West Bengal	n.a.	145	146	n.a.	104	111	n.a.	81	83	n.a.	41	48
7	**Indonesia**	Jawa Timur	n.a.	126	129	n.a.	91	100	n.a.	63	65	n.a.	28	37
13	**Indonesia**	Jawa Tengah	n.a.	208	209	n.a.	168	172	n.a.	72	73	n.a.	31	35
2	**Pakistan**	Sind	142	144	n.a.	102	110	n.a.	79	81	n.a.	102	47	n.a.
6	**Srilanka**	Polonnaruwa	134	136	n.a.	98	105	n.a.	71	73	n.a.	98	42	n.a.
4	**Thailand**	Suphan Buri	n.a.	141	144	n.a.	100	114	n.a.	78	81	n.a.	37	51
11	**Vietnam**	Thái Bình	n.a.	209	210	n.a.	113	118	n.a.	130	131	n.a.	34	39
12	**Vietnam**	An Giang	n.a.	208	209	n.a.	168	172	n.a.	72	73	n.a.	31	35
		Average	**138**	**158**	**163**	**100**	**114**	**123**	**75**	**81**	**83**	**100**	**37**	**43**
		Max	**142**	**209**	**210**	**102**	**168**	**172**	**79**	**130**	**131**	**102**	**47**	**54**
		Min	**134**	**126**	**129**	**98**	**91**	**100**	**71**	**63**	**65**	**98**	**28**	**35**

Table A5.5: *Overview of sugarcane trash delivery cost in USD/ton of cellulose for different chains*

			Pellet cost_including purchase cost (USD/ton cellulose)			Bales cost_including purchase cost (USD/ton cellulose)			Pellet cost_NO purchase cost (USD/ton cellulose)			Bales cost_NO purchase cost (USD/ton cellulose)		
HS	Country	Region	75 Kton	150 Kton	500 Kton	75 Kton	150 Kton	500 Kton	75 Kton	150 Kton	500 Kton	75 Kton	150 Kton	500 Kton
16	**India**	Uttar Pradesh	n.a.	177	179	n.a.	132	141	n.a.	89	91	n.a.	44	52
17	**Pakistan**	Punjab	145	148	n.a.	100	112	n.a.	86	89	n.a.	41	54	n.a.
19	**Thailand**	Uthai Thani	143	n.a.	n.a.	102	n.a.	117	84	n.a.	n.s.	44	n.a.	n.a.
20	**Indonesia**	Lampung	140	142	n.a.	93	98	n.a.	82	83	n.a.	34	40	n.a.
		Average	**143**	**156**	**179**	**98**	**114**	**129**	**84**	**87**	**91**	**40**	**46**	**52**
		Max	**145**	**177**	**179**	**102**	**132**	**141**	**86**	**89**	**91**	**44**	**54**	**52**
		Min	**140**	**142**	**179**	**93**	**98**	**117**	**82**	**83**	**91**	**34**	**40**	**52**

Smaller rice production areas are found specifically in Pakistan and Sri Lanka. In both countries there is not enough production of rice within a 100-km circle from any hub to source a large capacity cellulose dissolving plant. Sourcing small and medium size plants can be done in these countries but delivery costs are relatively high, particularly for bales.

Detailed cost calculation results for cellulose sourcing from sugarcane residues

For sugarcane residue, sourcing to cellulose dissolving plants the cost situation in 4 hub locations was investigated. Only in the Uttar Pradesh region of India, the sourcing of a combination with trash and bagasse was investigated. While, in all other hubs only sourcing of trash was investigated.

Table A5.5 represents sourcing only based on trash therefore it is concluded again that pellets are far more expensive compared to bales. Excluding the purchase cost, the lowest cost is for bales in Indonesia where they can be delivered to the plant gate for 34 and 40 USD/ton cellulose at a small and medium cellulose dissolving plant. For bales this amounts to 82 and 83 USD/ton cellulose, which is double the price of bales. The cost of sugarcane trash delivery is higher than for rice straw which is likely to be related to the spatial distribution of sugarcane and related collection cost.

Figure A5.2: *Distribution of cost over cost items for rice straw pellets and bales at different sourcing levels for Bangladesh*

Figure A5.3: *Distribution of cost over cost items for rice straw pellets and bales at different sourcing levels for Pakistan*

Figure A5.4: *Distribution of cost over cost items for rice straw pellets and bales at different sourcing levels for Thailand*

Figure A5.5: *Distribution of cost over cost items for sugarcane trash pellets and bales at different sourcing levels for Indonesia*

Figure A5.6: *Relationship between total delivery cost and distance to dissolving plant location at different sourcing capacities for sugarcane trash in Uttar Pradesh in India*

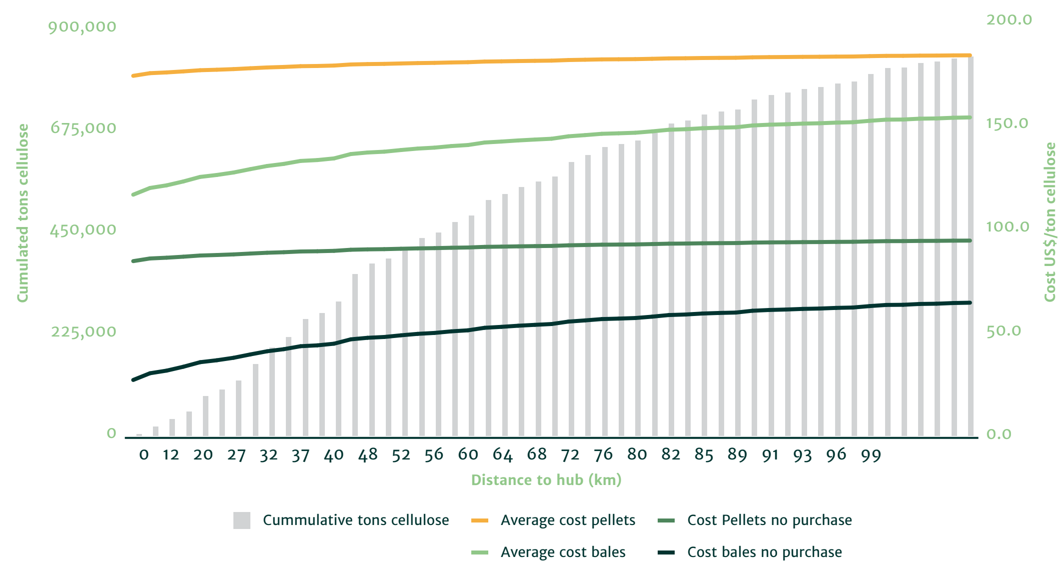


Figure A5.7: *Biomass delivery cost at different biomass chain options combining trash and bagasse to a medium size cellulose dissolving plant in Uttar Pradesh (India)*

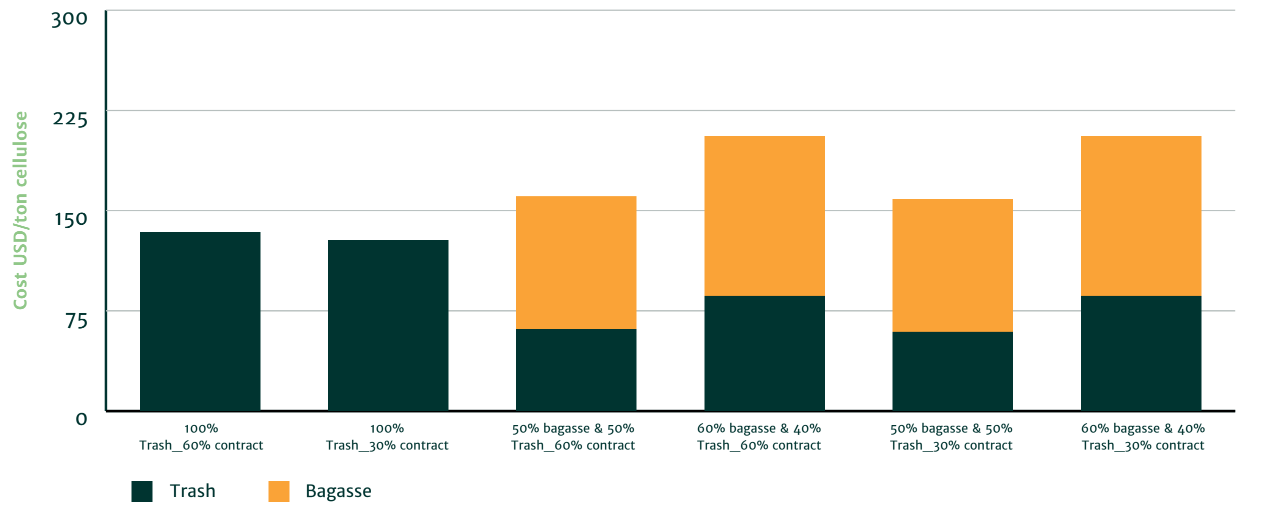


Figure A5.8: *Biomass delivery cost at different biomass chain options combining trash and bagasse to a large size cellulose dissolving plant in Uttar Pradesh (India)*

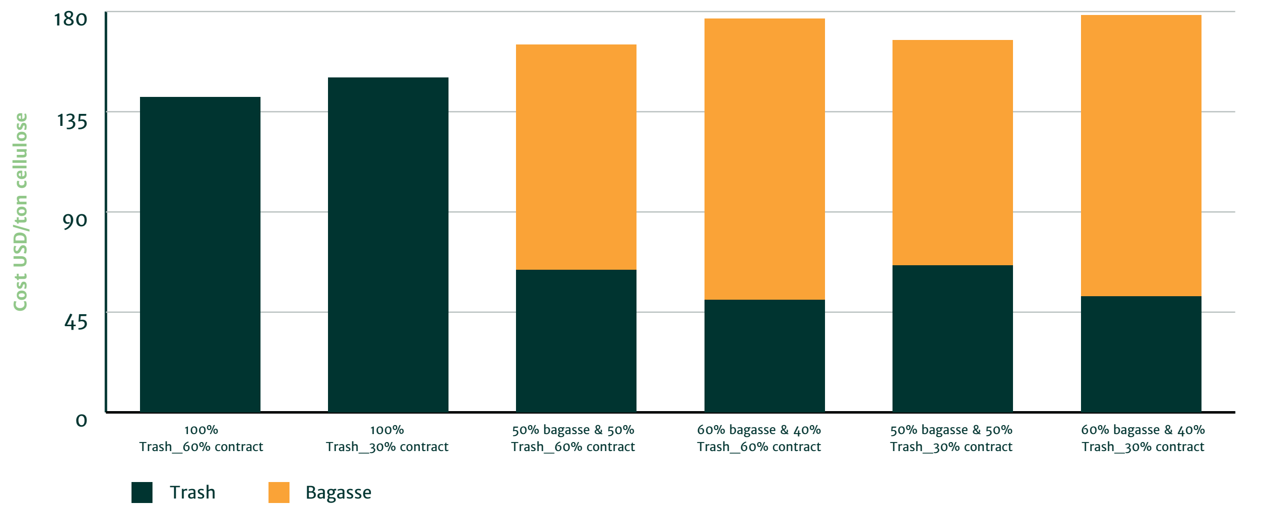
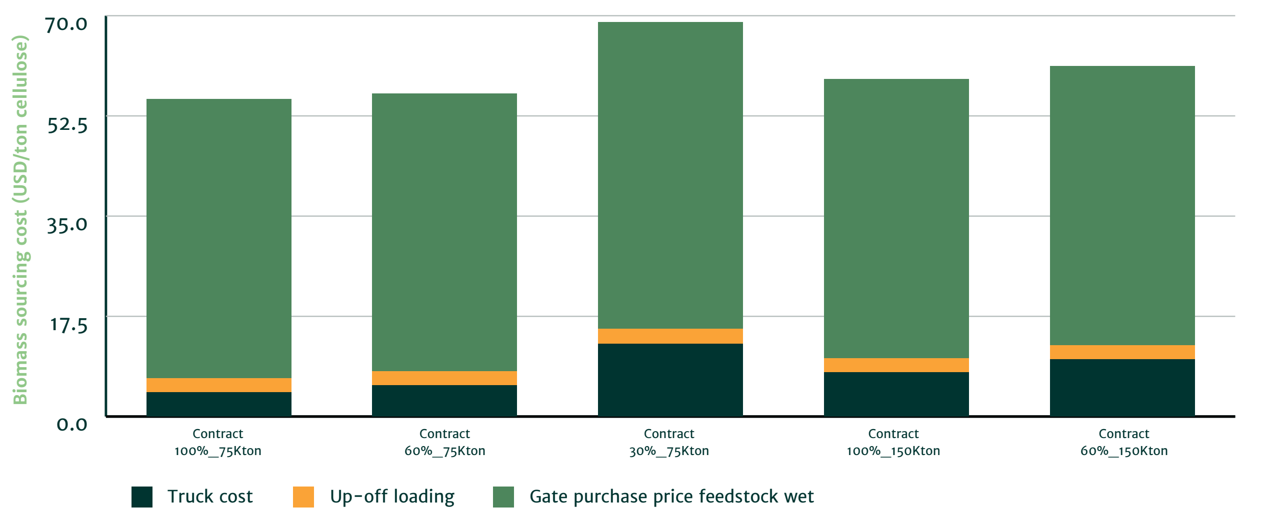


Figure A5.9: *bution of cost over cost items for EFB at different sourcing levels for Riau in Indonesia*



The cost composition for sugarcane trash delivery in Figures A5.4 and A5.5 illustrates large differences in cost levels between pellets and bales. Also, it is clear that in Indonesia cost levels are lower than in Thailand for the bale delivery. In the Uthai Thani hub in Thailand the availability of sugarcane is rather small which makes it impossible to source a 150-kiloton capacity cellulose plant at a contractibility level of 30%. In all other 3 hubs this is not a problem. Figure A6.6 illustrates that pellets and bales have very large cost differences and that these differences do not decline strongly with increased distance.

For Andhra Pradesh the cost in a combined sourcing with trash and bagasse was analysed. The results of this analysis are presented in Figure A5.7 for sourcing a 150-kiloton capacity plant and in Figure A5.8 for sourcing the largest cellulose dissolving plant. Trash delivered in bales is by far the cheapest sourcing solution. Since bagasse is more expensive to deliver any combination of sourcing with bagasse is more expensive.

Detailed cost calculation results for cellulose sourcing oil palm EFB

For the analysis of delivery cost for EFB to a cellulose dissolving plant the hub in the region of Riau in Indonesia on the island of Sumatra was chosen. Transport of EFB is quite expensive because of the high content of water. On the other hand, it is also concluded that the delivery cost of EFB to produce one ton of cellulose is cheaper than for rice straw, or sugarcane trash or bagasse unless large biomass demands are placed on the market as establishing a 500-kiloton cellulose dissolving factory in Riau would not be possible.

Annexure 6
Stakeholder mapping and analysis

Figure A6.1: *Major stakeholder groups and their associated stakes in the domain*

Stakeholder group	Associated stake
Farmers/farmer cooperatives	• Alternative uses of agro-residue • Addition to income from produce • Costs associated with residue removal (for e.g., labour)
Technology devel-opers	• Introduction of new/innovative technology for the market • Capacity to support mainstreaming of new/innovative technology • Energy intensity associated with new/innovative technology
Textile innovators and design experts	• Knowledge of essential fibre characteristics • Developing new textile fibre for market • Addition to income stream • Employment generation
Logistics network (for e.g. transport and storage)	• Establishing critical transportation connections in the delivery chain • Expansion in storage infrastructure • Addition to income stream • Employment generation
Textile processors and manufacturers	• Diversification in operations • Knowledge of new processes/technology • Associated capital inputs (technology, labour, upgrading facility etc) • Addition to existing income • Increased buyer (i.e. brands) interest regionally and globally
Apparel brands	• Enhanced sustainability standards • Ability to influence market demand • Improved consumer perception and base • First movers' advantage (through pilot models; limited) • Distinctive reputation among rival brands • Potential for business lobbying alternatives
Industry associa-tions	• Assess scope of aggregation for industry • Shared costs and benefits among members • Distinctive leverage with buyers and regulatory agencies
Agricultural experts	• Knowledge of suitable crops and their fibre characteristics • Ascertain sustainability of alternative feedstock through
Start-up organi-zations	• Entry into a niche market segment • Mainstreaming of alternative products • Improved market reputation and value • Larger income base

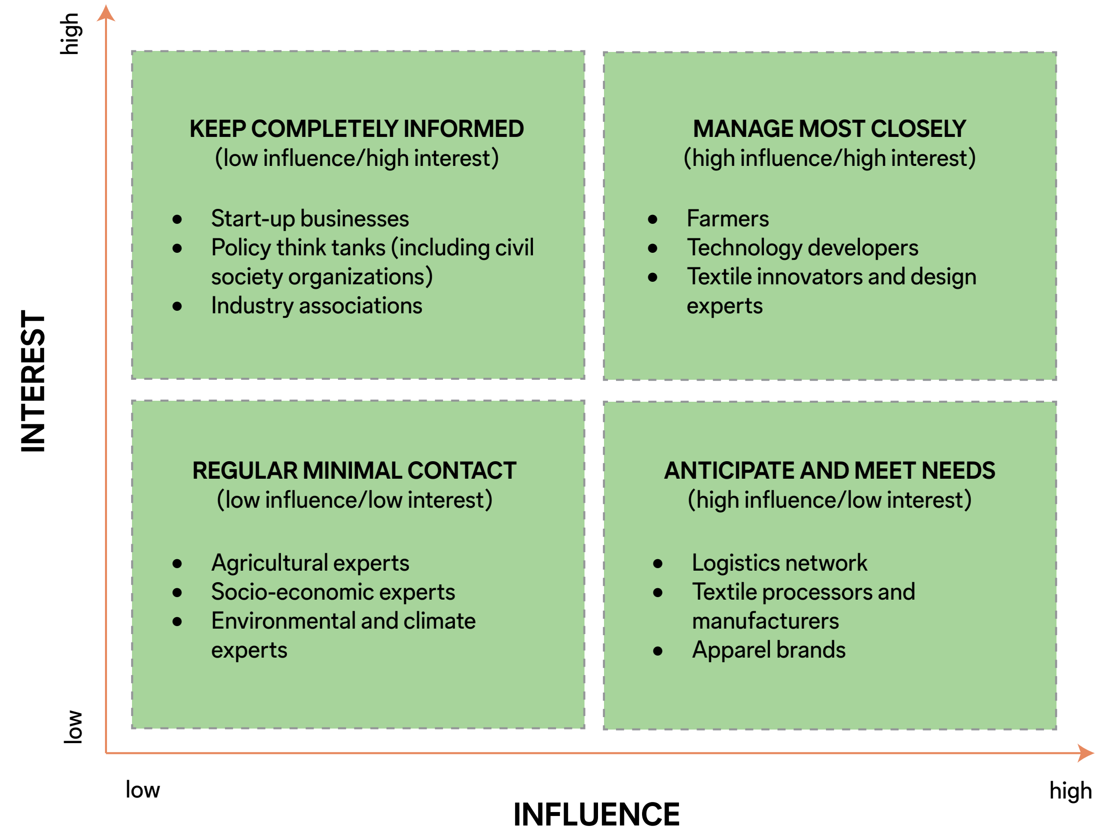
Stakeholder group	Associated stake
Government and its agencies	• Existing regulatory provisions for sale, storage and transport of agro-residue • Securing rural economy through like agriculture and allied activities • Effective management of agro-waste and residue, and reduced externalities like air pollution, environmental burden • Potential to introduce new conducive regulations
Social and envi-ronmental experts	• Knowledge of socio-economic implications on communities like livelihood generation, • Knowledge of environmental impacts like sustainable removal rates of residue, ecological burden • Knowledge of climate change on crop patterns and seasons • Potential to influence policy and lobbying for alternatives

The **interest-influence matrix** for stakeholders is divided into four major sections, depending on their degree of interest and influence, and different approaches are ascribed to engaging with the stake-holders that fall within these sections:

- Those with low influence and low interest: Regu-lar minimal contact
- Those with low influence and high interest: Keep completely informed
- Those with high influence and low interest: Anticipate and meet needs
- Those with high influence and high interest: Manage most closely

The figure below shows the influence-interest matrix for the stakeholders relevant for this project.

Figure A6.1: *Major stakeholder groups and their associated stakes in the domain*



Annexure 7
Questions sets for stakeholder consultations

SURVEY FOR FARMERS

(To be administered through farmer cooperatives, representative civil society organizations, agriculture universities and field workers)

Name of the farmer: ____

Location of field (state/region and country): ______________________________

Ownership-tenancy model for farm land

1. Are you an owner or a tenant?
2. Total land holding (in acre) __________
3. How much acreage is under cultivation in your farm?
4. Is your land irrigated or unirrigated
   a. If irrigated, what kind of irrigation system is used? (for e.g. groundwater, sprinkler, drip irrigation etc.)
5. What kind of cost-sharing model exists between the owner and tenants in your farm?
   a. Sharing of input costs (seeds, fertilizers, pesticides, equipment, irrigation)
   b. Sharing of logistics (transport, storage)
   c. Rent paid to owner
   d. Any loan extension/credit arrangement between owner and tenant
6. What kind of revenue-sharing model exists between the owner and tenant in your farm?
   a. % revenue shared between owner and tenant from sale of produce

Main crops cultivated

1. Which are the main sowing seasons followed by you?
2. List the crops grown during different seasons.
3. What kind of cropping pattern is followed by you?
   a. Mono-cropping (only one crop grown on the piece of land across seasons)
   b. Inter-cropping (growing two or more crops simultaneously on the same piece of land in a definite pattern
   c. Mixed inter-cropping (growing two or more crops simultaneously on the same piece of land in no definite pattern)
   d. Sequential cropping/Crop rotation (growing of different crops on the same piece in a pre-planned sequence)
   e. Any other pattern __________________________________
4. Which are the most resource-intensive crops, in terms of:
   o Water/Irrigation
   o Energy
   o Fertilizers
   o Pesticides
   o Manure
5. Does the crop cultivation involve heavy usage of chemicals and such inputs? If so, please list the chemicals used.

Yield, produce and revenue of the selected crop

1. Name of the selected crop: ____
2. Type of crop:
   a. Staple
   b. Non-staple
   c. Non-food

Input	Unit	Quantity used	Cost per unit	Total cost
Water/Irrigation cycles				
Seeds				
Fertilizers				
Pesticides				
Chemicals				
Electricity				
Type of farm equipment/ animal labour				
Human labour hours				
			TOTAL COST OF CULTIVATION	

3. What are the inputs, quantities and costs per unit quantity used in cultivating this crop?
4. What is the per acre yield of the selected crop?
5. What is the total production of the selected crop?
6. What is its market price (per quintal/per kg)?
7. How much is the total revenue from the produce? (5*6)
8. What is the net income from the produce? (Total revenue less total cost of cultivation)
9. How many family members can you support through this revenue?
10. Are you engaged in other economic activities to support your income? If yes, then specify the type and the income from each:
    a. Poultry farming
    b. Dairy farming
       i. cows
       ii. buffaloes
       iii. goats etc.
    c. Horticulture
    d. Any other ____
11. What trend has the yield of the selected crop shown over the last 5-10 years – increasing, decreasing or remained fairly constant?
12. Has the amount of water available been adequate to support cultivation of this crop over the last 5-10 years? If not, what changes have you experienced in terms of water demand? Have you adopted new methods of irrigation in the last 5-10 years? If so, please briefly describe them.

Agro-residues of the selected crops

1. Which parts of the selected crop are considered residue/waste?
   a. Husk/Hull
   b. Bagasse
   c. Leaves
   d. Stalks/straw
   e. Any other ____
2. What quantity of agro-waste/residue is generated for the selected crop per harvest cycle?
   o approx. % weight of the yield, or
   o approx. % weight of the total produce
3. What are the common methods of disposal and/or alternate uses for the agro-waste/residue from the selected crop?
   a. In case of commercial value:
      i. What are the ways of approaching the agro-residue buyer?
         o Individual direct contact
         o Group contact
         o Third party contact (middlemen)
         o Other, please specify: ______________________________
      ii. What part of the agro-residue is sold?
      iii. Who buys this agro-residue? (for e.g. Paper mills, Fertilizer companies, Brick kilns, or other industries/ sectors)
      iv. How much quantity of residue is sold per buyer?
      v. What is the per unit revenue earned for the sale of the residue?
      vi. What are the costs involved in selling this residue (i.e. labour/machinery for removal, power, transportation, storage)?
   b. In case of domestic use:
      i. What part of the agro-residue is used domestically?
      ii. Which domestic purposes are fulfilled?
         o Cattle feed
         o Manure/compost for the field
         o Fuel for domestic use
         o Any other ______________________________________
      iii. How much quantity of residue is utilized per domestic purpose?
      iv. Does the use of this residue allow you to save on other costs?
         o If yes, then how much do you save (approx.)?
      v. (in case of no current commercial value) Are you willing to sell this residue if you are paid for it?
   c. In case of disposal:
      i. Which are the common disposal methods for this residue?
         o Burning
         o Collection and transported to landfill
         o Keeping it in the field
         o Any other ______________________________________
      ii. Is there a logistics support (for e.g. transport) available for disposal and management of this residue? If yes, specify:
         o Government
         o Private
         o Local and informal, based on social relations
         o Any other ______________________________________
      iii. What kind of costs are involved in disposing this residue?
      iv. (in case of no current commercial value) Are you willing to sell this residue if you are paid for it?

FOCUS GROUP DISCUSSION ON CLIMATE CHANGE AND ITS EFFECTS ON AGRICULTURE

(to be conducted with farmers, agricultural universities and researchers)

1. Have you experienced crop failure in the last 5-10 years? If yes, how many times has this occurred?
2. To what reasons would you attribute crop failure? Please describe them briefly.
3. Have you experienced a change in the temperature pattern over the course of previous years (approx. 5-10 years)? If yes, what is the change?
4. Have you experienced a change in the pattern of precipitation over the previous years (approx. 5-10 years)? If yes, what is the change?
5. Here are a few indicators of change in temperature pattern. Please mention if you have experienced these:
   a. Increased summer days
   b. Frequent occurrence of heat-induced crop disease
   c. Frequent occurrence of heat-induced livestock disease
   d. Frequent occurrence of heat-induced human disease
   e. Emergence of new plant species/invasive species, in the form of weeds
   f. Quick disappearance of water sources/points due to high evaporation
6. Here are a few indicators of change in rainfall pattern. Please mention if you have experienced these:
   a. Late onset of monsoon
   b. Early onset of monsoon
   c. Reduced period of rainy season
   d. Erratic nature of rainfall
   e. Increased volume of rainfall in a short duration
   f. Long dry spells after onset of rains
   g. Crop failure due to water shortage
7. What kind of measures do you undertake in the following situations:
   a. Drought
   b. Flood
   c. Heavy rainfall
   d. Extreme heat
   e. Outbreak of pests and/or diseases

INTERVIEW QUESTIONS

For Agricultural Experts

1. Are you aware of any existing pilot models or studies that showcase the use of agro-residue as a textile fibre feedstock? If yes, please provide a brief description.

2. What are the critical success factors required in the agricultural setup to support the mainstreaming of agro-residue as an alternative raw material to produce textile fibres? (regulations, financing, logistics, more R&D, demand, low setting-up and input cost)

3. What kind of logistics network (from farm-to-roadside) is required to support the delivery chains for this initiative? How do the existing logistics arrangements fare in these respects? What changes can be recommended?

4. What kind of policy support and barriers exist currently that can affect the mainstreaming of agro-residue as a textile fibre feedstock, directly or indirectly? What opportunities can be created through policy modifications to support such initiatives? (prompts: cross-boundary regulations on transportation of agro-waste; recommendations for management and disposal of agro-residue; financing schemes for innovative technology development and scale-up; research grants)

5. What factors can act as barriers to this model in an agricultural setup? How can these be addressed?

6. In case of other uses for the agro-residue, what are some key anticipated trade-offs in shifting the supply of residue from those uses to the proposed use? What are the costs associated with these trade-offs?

7. How would these models affect the farming practices of the source crops (land use pattern; crop rotation practices; use of fertilizers and chemicals; irrigation)?

8. What could be some other unintended consequences of mainstreaming this sourcing model? How would this impact the sustainability of these models?

Technology

1. What kinds of innovative technologies/processes are available, both at pilot stage or commercial use, to process agro-residue to produce textile fibres? Please describe them briefly.

2. Which kinds of agro-residue can be processed using this technology? What is the minimum lot size of agro-residue required for processing in this technology? What is the subsequent quantity of output (fibre) generated from this technology/process?

3. What are the costs involved in developing this technology/process (raw materials, water, energy, labour)? How will these be affected when the technology is scaled-up? Will there be any additional costs involved in scaling up? If so, what kind?

4. What are the key success factors necessary to scale-up this technology/process to be used at a commercial level (for e.g. a basic minimum level and regular supply agro-residue; availability of inputs; infrastructural requirements; financing etc.)?

5. What are the current barriers/challenges affecting the scaling-up of production and use of this technology? In what ways can these be addressed?

6. What is the future outlook for this technology in the textile industry? How does it compare with the other widely-used technologies in textile manufacturing? What modifications can make this innovative technology/process more feasible for use?

7. What are the environmental impacts associated with the development and use of technology (for e.g., air pollution, effluent release, energy demand)? How can these be mitigated/abated?

8. What could be the unintended consequences of mainstreaming the use of this technology/process?

Fibre

1. Which types of agro-residue are being currently utilized to produce textile fibre? How prevalent/at what scale are these residues being used?

2. What are the costs involved in the production of these fibres (for e.g. removal from field, transportation, storage, stages of processing, inputs like water, energy, chemicals, labour)?

3. What are the key characteristics and quality features of such fibres? What are their current textile applications? Is there a scope for expanding their future applications? If so, what are these potential applications?

4. What are the current textile applications of the fibres generated through this technology? Are there other potential applications in textiles and garments? If so, what will enable their realization?

5. How do these fibres compare with the more conventional and widely used in textile production (on parameters like quality, applicability, cost of production, price, ease of sourcing etc.)?

6. Which factors will positively bolster the mainstreaming of these fibres in the textile industry?

7. What are the main barriers and challenges to the commercialization of these fibres? How can these be addressed? What kind of challenges can arise in the future?

8. What is the potential for recycling, reuse and disposal of the textiles made from these fibres, after their use? How do they impact the environment and the climate?

Commercialisation & Market Perspectives

1. Are there any apparels brands/innovators involved in processing agro-residue for fibre/utilizing the fibres made from agro-residue to produce textiles? If so, please briefly describe them.

2. In which textiles/apparel segments are these fibres being currently used? Is there potential to expand these applications? If so, how and in which area can this be done? (probe into any modifications required in these fibres)

3. How do products made from these fibres fare in comparison with the products made from more prevalent/conventional fibres in terms of their market demand and ability to compete (includes factors like cost of production, price of fibre, brand awareness, demand, consumer awareness, typical consumer base)? Are there any large brands using it in their production? If so, which ones are these?

4. How do these fibres compare with the other conventional and widely-available fibres on key sustainability parameters (ease of reuse, recycling, disposal; energy demand; resulting emissions from production; intensity of water use; use of chemicals and dyes; health and well-being of workers)?

5. How do the apparel brands perceive the current market value and demand of textiles made from agro-residue? How are these expected to take shape in the future?

6. What are the pre-requisites for large brands to take up these fibres into their main production lines (for e.g. investments in skill, technology, infrastructure; regular supply of agro-residue; established delivery chains; marketing and building consumer awareness etc)? How can economies of scale be achieved in this?

7. How do the existing logistics arrangements (from farm-to-roadside and roadside-to-mill) support this model? What changes can be recommended? What role can the brands/textile processors play in this?

8. What role can aggregation mechanisms play in supporting this model? How feasible are they in the current textile supply chain context?

9. What are the key barriers and challenges to the mainstreaming of these fibres? How are these expected to change in the future?

10. What role can international standards, policies and regulations for textile manufacturing play in support the large-scale commercialization of these fibres?

11. What are the other kinds of innovations expected to take place in the textile industry to enhance its sustainability? How does this initiative (agro-residue as textile fibre feedstock) compare with them (any scope of converging, complementing or being overshadowed)?

12. What could be the unintended consequences/externalities (positive and negative) for the textile industry stakeholders arising from the mainstreaming of these fibres?

Socio-Economic and Environmental Implications

1. What changes could occur in the prevailing socio-economic conditions in rural areas due to the commercialization of use of agro-residue as textile fibre feedstock (economic set-up, new sources for livelihoods, social relations etc.)?

2. What kind of environmental impacts are expected to follow the scaling-up of use of agro-residue as a textile fibre feedstock (for e.g. land use pattern, transportation, energy use, water use, soil quality)? How can these be addressed?

3. What role will climate change and its effects (like change in weather patterns, irregular monsoons) play in the use of agro-residue in textile industry? Conversely, will this transition mitigate some effects of climate change?

4. How do the existing intra-regional policies, international treaties and agreements enable and/or hamper the transition from conventional fibres to agro-residue for textile fibres?

Annexure 8
Climate change and associated impacts on the shortlisted crops

Table A8.1: *Climate change and associated impacts on the shortlisted crops*

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
India	Rice	• ⊠Impact of climate changes were assessed in Kerala and it was found that for every 1° C increment the decline in yield is ~6%. Decrease in rainfall leads to a yield loss of constant rate of 8% per 2mm/day, upto about 16mm/day (Saseendran et al. 2000). • ⊠Study conducted on the Indian states reveals that climate change will reduce the overall rice yield by 3-5% under the medium emission scenario and 3.5-10% under the high emission scenario. Several adaptation strategies such as direct seeding of rice, supplemental irrigation, alternate wetting and drying, improved management practices to increase rice yield etc., are suggested (K 2017). • ⊠High increase in CO2 and low increase in temperature may increase rice yields while high increase in temperature and low increase in CO2 may cause dip in rice yield. Necessary steps such as introducing varieties that can withstand fluctuating temperatures must be implemented soon (Vyankatrao 2017). • ⊠Study conducted in Keonjhar district showed that increase in maximum and minimum temperatures beyond an optimum for rice production lead to a decrease in yield and minimum temperature changes had more profound negative impacts as compared to maximum temperature changes (Ray, Roul, and Baliarsingh 2018). • ⊠The Vector Autoregression model (Farook and Kannan 2016) was employed to study the climate change impacts on rice yield in the Kharif and Rabi seasons, and inferred that total rainfall is perceived to adversely affect the Kharif rice yield, while in the case of Rabi rice yield, average maximum temperature and total rainfall have negative effects on the yield and average minimum temperature on the other hand affected the yield positively.	• ⊠To sustain the food production in coming decades, the rice production level needs to be increased every year by at least 2 million tons (Wanjari et al. 2006). This target may be achieved through cultivation of hybrid rice, and it is possible to bridge the gap between projected demand and the current level of production. • Urgent need for developing more Nitrogen-use efficient varieties and rice production technologies demanding lesser water, labour, nitrogen and pesticides (Prasad, Shivay, and Kumar 2017). • ⊠Integration of non-local freshwater dynamics with local rainfall variability is needed to determine the soil moisture conditions in rice fields for yields, assessment, modelling and forecasting (Zampieri et al. 2018). • ⊠Agricultural development policy seeking to make rice farming more resilient to climate hazards should identify and tackle contextual factors that contribute to vulnerability (Duncan et al. 2017). • Crop/varietal diversifications help farmers to grow two or more crops/varieties in a year where they could only grow one crop (Lal et al. 2017). Early maturing rice varieties can be combined with these in order to take advantage of the residual soil moisture available.
	Wheat	• An analysis of rainfall and temperature changes using the SWAT hydrological tool over the Gomti river basin, during the wheat growing period showed that wheat growing season rainfall was projected to decrease in the range of 5.1–26.4, 1.9–15.4 and 7.6–16.7 % during 2020s, 2050s and 2080s, respectively and a consequent improvement in irrigation facilities is necessary to maintain profitable yield (Abeysingha et al. 2016). • Vulnerability mapping done to assess the resilience of regions to variability in monsoon conditions saw that Jharkhand was one of the most vulnerable regions, while Punjab is one of the least across wheat producing ecologies (Sendhil et al. 2018). Also, magnitude of vulnerability is high in five regions (contributing 19% of total production), moderate in six regions (12% production) and low in five wheat growing regions (69% production). • Study conducted on assessment of the impacts of climate change on Wheat production in Uttar Pradesh and Haryana suggests that increase in rainfall, maximum and minimum temperature have a negative impact on production. Non-climatic factors also seem to play a significant role (Kumar et al. 2020). • A study to quantify the role of different environmental factors and management practices on wheat production in India (1980-2016) show that the [CO2], irrigation, fertilizers, and temperature forcings have led to 22 Mt (30 %), 8.47 Mt (12 %), 10.63 Mt (15 %), and -13 Mt (−18 %) changes in countrywide production, respectively (Gahlot et al. 2020).	• ⊠Favourable growing season temperatures, moderate to high fertilizer application, high availability of irrigation facilities, and moderate water demand make the Indo-Gangetic Plain the most productive region, while the arid north-western region is the least productive due to high temperatures and lack of irrigation facilities to meet the high-water demand (Gahlot et al. 2020).

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
India	Banana & Plantain	• Higher temperatures (31-32°C) increase the rate of plant maturity in banana thus shortening the bunch development period (Malhotra 2017). • For 27 countries accounting for 86% of global dessert banana production, a changing climate since 1961 has overall increased annual yields but these could dampen to 0.59t/Ha and 0.19t/Ha by 2050 under the climate scenarios for RCP 4.5 & 8.5 respectively, driven by declining yields in the largest producers and pathways (Varma and Bebber 2019). Securing future supply to non-producing countries, where banana consumption is an important contributor to dietary diversity, is likely to require a reorganization of the export market. • Investments targeted at yield growth appear to be more effective than marketing improvements in alleviating production constraints and in strengthening the role of Banana crops in future food systems (Petsakos et al. 2019). • Leaf spot disease in banana crops in Jalgaon region of Maharashtra has started appearing and can be attributed to climate change (Ravi and Mustaffa 2013).	• Novel technologies such as microwave, vacuum, infrared, high pressure, pulse electric, irradiation etc. have resulted in better quality products in terms of nutrient retention, enzymatic and microbial inactivation as well as in replacing thermal operations like blanching, pasteurization, sterilization and dehydration (Mohapatra et al. 2011). • Study conducted on assessment of post-harvest losses showed that overall losses in banana comprised of (6.81%) loss at field level, (3.90%) loss during transport (Jadhav et al. 2020). The minimum (1.56%) post-harvest losses in banana were recorded during assembly market/wholesale market. The losses to were recorded during storage and ripening was (3.40%). The highest loss (14.12%) was observed at retailer level.
	Coconut	• Negative impacts on yield of coconut are projected for Andhra Pradesh, Orissa, West Bengal, Gujarat and parts of Karnataka and Tamil Nadu, while overall productivity in India is projected to increase in future climate scenarios (Naresh Kumar and Aggarwal 2013). • Natural calamities like droughts and cyclones have affected the productivity of coconut by about 3500nuts/Ha/yr in India for four years (Hirpo 2019). • Rainfall, evapotranspiration, solar radiation, sunshine hours, relative humidity and wind velocity are the major climatic variables that influence the yield when other external factors such as fertility, management, pests and diseases are non-limiting (Peiris, Thattil, and Mahindapala 1995). • Climate change in the Western Ghats, coastal districts and NE regions is projected to significantly affect crop production. The impacts are crop specific and simple adaptation strategies such as change in variety and altered agronomy, high input delivery and use efficiency can offset the negative impacts of climate change (Naresh Kumar et al. 2011).	• To increase the shelf-life of the coconuts the nuts have to be harvested carefully with intact perianth and without any breakage of nuts (Haseena, Bai, and Padmanabhan 2010). The quality of minimally processed nuts deteriorates earlier than non-dehusked nuts during storage.
	Maize	• Empirical results of a study carried out in Telangana show that average minimum temperature has a significant unfavourable impact on Maize yield (Guntukula and Goyari 2020). Furthermore, rainfall and minimum temperature are risk-shrinking factors, but the maximum temperature is a risk-enhancing factor for the maize yields during the study period. • Maize yields in monsoon are projected to be adversely affected due to the rise in atmospheric temperature (Byjesh, Kumar, and Aggarwal 2010); but increased rainfall can partially offset those loses. Developing new cultivars in changed climate scenarios similar to that of current varieties in present conditions could be an advantageous adaptation strategy for minimizing the vulnerability of maize production in India. • Comparing data from different models suggests that future yield losses are projected for Maize and unless plant breeders are able to produce new hybrids with improved traits, the forecasted yield losses for Maize will only be mitigated by agro-management adaptations (Fodor et al. 2017). • According to a study conducted, Maize yield will decline by 29% in the mid-century, but this can be offset through improved management as adaptation strategies (Ahmad et al. 2020).	• Double mulching technology involving maize stover mulch and fresh biomass of ragweed is a viable option for improving soil, crop and water productivity under rainfed hill ecosystems of eastern Indian Himalayas (Ngangom et al. 2020).

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
India	Okra	• Study reveals that increase in temperature leads to a subsequent drought and increase in salinity, that may negatively impact the cultivation (Ayyogari, Sidhya, and Pandit 2014). Increase in CO2 may increase crop yields due to increased CO2 fertilization, but decreases after some extent. • Climate change conditions can facilitate the spread of plant viruses and other diseases (Krishnareddy 2013). A less predictable climate condition will cause uncertainty in decision making over the timing of control measures, particularly crops grown in the regions where climate is too warm or under drought stress may tend to become physiologically weaker to withstand infection. • Increased temperature and humidity facilitate growth of pest insect population that can cause severe damage resulting in lowering the yield of crop (Rawat, Karnatak, and Srivastava 2020).	• Plant-based stress detection based on leaf photosynthetic attributes could be utilized for enhancing water use efficiency at specific growth stage and to help in for devising agricultural water management options with the incorporation of spectral reflectance-based indicators in different crops (Chaturvedi et al. 2019). • Organic source of nutrients could be a better option in terms of optimum growth, yield and profitability of the crop (Dutta, Kalita, and Maibangsa 2020).
	Pineapple	• Changes in climate have significant impacts on pineapple cultivation, price fluctuation and diseases during flowering stage in Kerala (Thomas and Dinesh 2020). Around 50% of the crop was affected by various diseases post flooding that lead to degradation of the fruit. • Production of pineapple has been affected negatively in Meghalaya during the time periods of low rainfall or droughts in the state, hence appropriate adaptation strategies are required to cope with these impacts (Sheikh et al. 2018).	• Malpractices such as colouring, oiling, sweeteners and hormone injections followed by retailers are mainly profit targeted. The involvement of farmers, retailers, consumers, scientists, policy makers and government agencies is required to address this issue (Panghal et al. 2018).
	Seed Cotton	• Cotton productivity in Northern India is projected to marginally decline owing to decrease in rainfall (Hebbar et al. 2013). Adaptive measures such as changes in planting time and more responsive cultivars may further boost cotton production in India. • Study shows that higher temperatures in already hot areas may hinder cotton development and fruit formation (Ton 2011). Rain-fed cotton production may suffer from higher climate variability, leading to periods of drought or flooding. Irrigated cotton, particularly in northern India, may suffer from lower water availability due to upstream reduction of snow and ice from Himalayan and Tibetan plateau glaciers and snowfields.	• Relay planting increased seed cotton yield by 12% in comparison to the conventional method (Singh et al. 2017). • Effective disease and pest control measures need to be developed to check the perennial pest infestation of cotton in the state of Haryana (Seidu 2018).
	Sorghum	• Study on assessment of vulnerability of sorghum cultivation to climate change impacts shows that the yield loss may be huge for locations where the current temperatures are already high and the rainfall is low, whereas for places where the current temperatures are relatively low with moderate rainfall, the yield loss is likely to be lesser (Srivastava, Naresh Kumar, and Aggarwal 2010). Adaptation strategies suggested are the implementation of more resilient varieties and shifting of planting times. • Simulations suggest that Sorghum is more sensitive to availability of nutrients and soil water under rainfed conditions (Rao et al. 1995). • Increase in temperature and rainfall beyond a threshold level can negatively affect the sorghum yield in the future (Saravanakumar 2015).	• Hybridization with a wild species of sorghum may improve stress tolerance of the species. However, this is a challenging process because of the lack of genetic information on the wild sorghum species and the complexity involved in the process of introgression (Ananda et al. 2020).
	Sugar-cane	• The most significant challenges to sugarcane are increases in frequency and intensity of extreme weather events, especially drought during climate change (Zhao and Li 2015). Improving resilience of sugarcane production systems to climate change requires the protection of the natural resource for sustainability. • Simulations using the CANEGRO- sugarcane model to assess the impacts of climate change on sugarcane in different combinations of elevated temperature and CO2 concentrations revealed that sugarcane fresh stalk mass mostly increased but sucrose mass decreased. In general, water stress conditions combined with the projected increase in temperature adversely affected the sugarcane (Sonkar et al. 2020). • Average maximum temperature in summer and average minimum temperature in rainy season have a negative and statistically significant effect on sugarcane productivity (Kumar 2014). • Significant effect on sugarcane yield is expected in the future owing to its sensitivity to temperature, rainfall, solar radiation etc. Advanced agronomic measure including development of varieties of sugarcane more immune to climatic conditions is necessary (A. K. Srivastava 2012).	• Study conducted reveals that there could be variability in cultivars of sugarcane with respect to deterioration during long harvest-to-crush periods at both high and low temperatures. Losses in stalk weight and sucrose content can also simply be reduced by spraying with water and covering with organic trash if there is a delay in supply and processing (P. Singh, Singh, and Singh 2020).

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
Bangladesh	Rice	• Sea level rise and salt water intrusion could reduce yield by 15.6% in nine coastal sub-districts (Dasgupta, et al. 2017) • Impact of temperature rice varies seasonally and regionally. Between 1981-2010 on an average, for 1°C rise in temperature the yield of Boro rice in projected to increase by 1.49%, while that of Aman and Aus rice are to decline by 6.85% and 0.18% respectively. The net impact being a decline in productivity and production (Lewis and Ostendorf 2017) • Rainfall during monsoon months has an increasing trend and dry months (November to March) has a slight decrease. This would increase the moisture stress on Boro rice cultivation. (Md Abiar Rahman 2017)	• Adoption of irradiation seeds to significantly improve time to breed new and improved plant varieties (Jawerth 2017) • SRI being adopted in the state country since 1999-2001 (SRI International Network and Resources Center (SRI-Rice) 2015) • Bangladesh Agricultural University has also developed new method- Boro paddy cultivation technique for direct dry seeding (Similar to SRI) (Siddique 2016) • Studies suggest the need to reschedule crop calendar and cropping pattern along with introduction of temperature and moisture stress tolerant rice varieties. (Md Abiar Rahman 2017)
Sri Lanka	Rice	• Simulation of climatic conditions over different varieties of rice revealed that both wet zone and dry zone rice produce decreased, thus imposing the need for adaptation measures to be implemented in the future (Amarasingha et al. 2018). • Increase in temperatures of more than 2-4° C can have upto a 30% decrease in yield. Variations in precipitation can be reduced in impact by increased use of irrigation (Ratnasiri et al. 2019). • The increase in average temperature for 2040–2070 from that of 1980–2010 ranged from 1.1–2.4 °C for Maha and 1.5–2.8 °C for Yala seasons, in a projection made over Northwestern Sri Lanka (Zubair et al. 2015). Respective projected yields of rice were lower for both the seasons. • Subtle increases in July maximum and minimum temperatures have a negative impact on the “Yala” paddy yields in most of the divisions namely, Anudhapura, Batticaloa, Hambantota, Jaffna, Kandy and Mannar (Shanmuganathan 2013).	• Recent study on pesticide use by farmers showed that most were using them as an adaptive measure to counter any possible loss to high yielding rice varieties, and not due to prior knowledge about them (Horgan and Kudavidanage 2020).
Pakistan*	Rice	• Increase in MMXT negatively impacts rice production while increase in MMNT impacts positively. (Usman Shakoor 2015) In net the rising temperatures is likely to cause drop in rice production by 15-20% towards the end of century (due to drop in crop yield) (Muhammad Mohsin Iqbal 2009) • 80% of the Pakistani rivers derive water from Hind-Kush Himalayan glaciers. Rising temperatures would cause increased river flows and flooding in next 2-3 decades, followed by a decreased flow. The large variability of Himalayan river flows will make irrigated areas more vulnerable to production losses. (Muhammad Mohsin Iqbal 2009) • Variability in frequency and intensity of rainfall will adversely affect rainfed areas. (Muhammad Mohsin Iqbal 2009)	• Direct seeded rice cultivation is being promoted in the country to reduce water and labour use by 50%. (S Marasini 2018) • Studies are being undertaken in Gilgit-Baltistan region to assess snowmelt runoff and glacial resource potential under climate change scenarios (Pakistan Agriculture Research Council (PARC) 2019) • It has been importing HYV seeds from India for quite some time (AgroBusiness Times 2018). The government has set target yeild for various crops and has plans for importing Climate resilient high yielding varities of seeds to increase productivity and profitability of farmers (Talpur, et al. 2018).
	Wheat	• The rise in temperatures is likely to cause drop in wheat production by 6-8% towards the end of century (due to drop in crop yield) (Muhammad Mohsin Iqbal 2009) • Northern mountainous region will have an increase in yield of 40-50 %, improving local food self-sufficiency. But the region accounts for only ~2% of the national production. (Muhammad Mohsin Iqbal 2009) • Rising temperatures would cause increased river flows and flooding in next 2-3 decades, followed by a decreased flow. The large variability of Himalayan river flows will make irrigated areas more vulnerable to production losses. (Muhammad Mohsin Iqbal 2009) • Variability in frequency and intensity of rainfall will adversely affect rainfed areas. (Muhammad Mohsin Iqbal 2009)	• Studies are being undertaken in Gilgit-Baltistan region to assess snowmelt runoff and glacial resource potential under climate change scenarios (Pakistan Agriculture Research Council (PARC) 2019)
	Seed Cotton	• Studies in southern Punjab indicate an increase in the number of days for maturity of cotton. While there is an increase in cotton yield due to projected increase in precipitation and CO2 concentrations. (Asad Amin 2018) • Changes in temperature and precipitation would have negative impact on cotton production but there are significant district wise variations in crop productivity. (Rehana Siddiqui 2015)	• It has been importing HYV seeds from India for quite some time (AgroBusiness Times 2018). The government has set target yeild for various crops and has plans for importing Climate resilient high yielding varities of seeds to increase productivity and profitability of farmers (Talpur, et al. 2018). • Inadequate access to timely weather forecasts is increasing losses for farmers. In 2016, a text message service- Telecotton , was launched to address this gap. But its adoption among farmers remains poor (Reuters 2019).

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
Indonesia*	Rice	• For every 1° C rise in temperature rainfed paddy yields to decline by 14.4% and that of irrigated paddy field by 11.1% (Yuliawan and Handokob 2016) • For every 1°C rise in temperature there is lower quality of rice and 10-25% decline in production (Ministry of Foreign Affairs of the Netherlands 2018) • In some coastal districts of Java, inundation due to sea level rise is expected to reduce rice production by 95% (Ministry of Foreign Affairs of the Netherlands 2018) • A 30-day delay in monsoon predicted. Which may prolong the "hunger season" and prevent farmers from planting two consecutive rice crops (Ministry of Foreign Affairs of the Netherlands 2018) • 55% of the rice in Indonesia is produced in islands of Java and Bali. Thus, climate change impacts and adaptation strategies in them have the largest bearing on food security in the nation (Ministry of Foreign Affairs of the Netherlands 2018) • In El Nino years rice harvest area decrease while in La Nina the harvest area increased. The changes are much higher for wet paddy fields than dry paddy fields. (Aldrian, et al. 2012) This indicates increased crop losses during El-nino years and vice-versa for La-nina. • Studies in Indonesia indicate that female farmers have a higher climate change resilience and ability to withstand climate shocks (Rondhi, et al. 2019)	• The continued diversion of eco-sensitive peatlands for paddy cultivation, as a part of rice estate project, is a major issue that the national government is yet to change its trajectory on it (Budiman 2020) • Terrace farming of rice in Bali is one of the successful traditional farming practices by farmer organisations called Subaks (Resilience Alliance n.d.). Since 2012 it forms part of the UNESCO World Cultural Heritage cite, and it has lot of potential for sustainable climate resilient agriculture (UNESCO 2012). • The traditional methods of Rice- Fish farming is being emphasised in the country to diversify farmers income, ensure better water management, reduce GHG emissions and shift to organic farming methods. FAO is an active participant in such initiatives. (Cruz 2001, Beau Damen 2018)
	Maize	• Increase in yield of corn in projected with 25% increase in the value of crop (Hecht 2016) • Areas of maize cultivation with increased rainfall will have positive effect in yield, while those with higher temperatures are to have reduced yields. The net result being positive (Hecht 2016) • In El Nino years maize harvest area decrease while in La Nina the harvest area increases. (Aldrian, et al. 2012)	• Some studies suggest shifting to maize cultivation in areas projected to have increased rainfall like Lampung and Gorontalo province (Hecht 2016)
	Pine-apple*	• Though no studies were found on the impact of climate change on pineapple in Indonesia, there are some examples from other countries. Studies on smallholder pineapple farmers in Ghana indicate a steep drop in net revenues per hectare for a 1°C increase in temperature, and substantial increase in it for a 1mm increase in rainfall. The studies in rainfed areas indicate the susceptibility of the crop to climate change. (Portia Adade Williams 2017)	
	Oil Palm	• Increased temperatures may lead to inability of Oil palms to grow in some areas. (R. Russell M. Paterson 2015) • Oil Palm growth could be severely impacted by climate change. A gradual decline in suitability of regions for palm cultivation (like islands of Papua and Kalimantan) is projected by 2030 which is to become more pronounced by 2100 (R. Russell M. Paterson 2015) • Increased heat stress on oil palm is projected on islands of Sumatra, Java and Borneo. While increased moisture stress is projected on islands of Java, Lombok, Sumbawa, Sumba and East Timor, among others. (R. Russell M. Paterson 2015) • Water requirements are estimated to increase by 10% for every 1°C rise in temperature. (Suresh 2013)	• Diversion of tropical forest areas (deforestation) and peat land for palm oil cultivation, among other crops, is a major cause of GHG emission in Indonesia. (R. Russell M. Paterson 2015)

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
Thailand	Rice	• Expected reduction in mean rice yield (4.56-33.77%) and subsequent increase in production variability (3.87-15.7%) due to overlying climatic conditions like increase in temperatures and precipitation (Sinnarong et al. 2019). Adaptation strategies to be implemented to counter risks to food security. • Integrated Assessment Model predicts by 2050 Thailand will experience drier weather and consequent increased water stress. Higher concentration of CO_2 aids crop yield, however resultant higher temperatures will nullify this effect (Sekhar 2018). • Irrigation requirement for different Rice varieties is projected to increase (Blue WF) in order to maintain profitable yield as an impact of future climate conditions (Shrestha, Chapagain, and Babel 2017). • Rain-fed rice yields expected to decrease while irrigated rice yield set to increase, as result of increasing trend of irrigation water use (Felkner, Tazhibayeva, and Townsend 2009).	• To avoid a larger water footprint, large scale farming is more suitable and should be encouraged as it helps mitigate climate impacts and return greater yield compared to individual farming (Arunrat et al. 2020). • Shifting of planting dates and fertilizer application dates forward by one week and supply of sufficient irrigation during Rice flowering stage could significantly increase rainfed rice yield to potential yield capacity, under various projected climatic scenarios in the 2080s (Boonwichai et al. 2019). • Fertilizer, seed, and pesticide use can be reduced in intensive lowland irrigated rice growing areas of Thailand by following best management practices promoted by the government with no yield penalty (Stuart et al. 2018). The improved practices were found to reduce costs and increase profit.
	Sugar-cane	• Future sugarcane yield expected to decrease by 23.95-33.26%, harvested area by 1.29-2.49% and production by 24.94-34.93% during 2046-2055 period, with largest drops expected in the eastern & southern sections of the central region (Pipitpukdee, Attavanich, and Bejranonda 2020). • Sugarcane cultivation is at risk of flooding in the central regions, while there is a drought risk in the northeast (T-PLAT (Thailand Adaptation Information Platform), n.d.). • Study on socio-economic impacts of sugarcane production in Nakhon Ratchasima show that cultivation practices, natural phenomena and relationships between the sugar factory and growers play an important role, for e.g., mechanized planting & harvesting contributes to decreased labour use (Sawaengsak and Gheewala 2017). • Employment wages of workers in sugarcane farms mainly depend on the yield, employment types (permanent or temporary) and skills (Sawaengsak, Prasara-A, and Gheewala 2020). Additional training must be provided for workers to ensure easy transition from manual to mechanized harvesting.	• Drip irrigation techniques can help maintain sustainable yield in times of water scarcity (Silalertruksa and Gheewala 2018). • Through better management practices, farmers can reduce the amount of physical inputs they are currently using in their farms and ultimately, they can reduce the cost of production of sugarcane without compromising the yield which will lead to increase in profits (Ullah et al. 2019). • Reducing nitrogen fertilizer application and increasing the nitrogen fertilizer use efficiency can significantly reduce both GHG and PM2.5 emissions (Mudi et al. 2016). • Mechanized harvesting contributes to loweset GHG emissions but highest harvesting cost (Pongpat, Gheewala, and Silalertruksa 2017).
	Pineapple	• Carbon footprint of pineapple for a 158 Ha area of cultivation was found to be 172 g CO_2eq/kg of fresh pineapple with a main contribution from fertilizer usage (58-79%), depending on the size of the farm (Usubharatana and Phungrassami 2017). • High air and soil temperatures can affect yield of pineapple, along with insufficient precipitation or irrigation networks (Manik et al. 2019). • Price incentives as well as price stability and market certainty via contract farming are effective policy measures to ensure good agricultural practice of Pineapple farming in Thailand. Individual growers not under contract are less likely to follow govt policy of agricultural practices (Sriwichailamphan et al. 2008).	

Country	Crop	Impact of climate change on crops and farming*	Challenges and new trends in cropping practices**
Vietnam	Rice	• Sea level rise threatens the low-lying rice cultivating regions in Mekong river basin (United Nations 2015) • Increased salinity due to salt water intrusion caused by droughts in river floodplains (particularly on tributaries of Mekong river) (Corben 2016) • Without appropriate interventions rice production could drop by 18% by 2030 (Le 2016) • Reduction in yield of winter season rice and increase in summer season rice is projected (Deb and Shrestha 2014) • 1° C increase in temperature would shorten growth cycle of rice by 5-8 days (FAO 2011) • Potential of increased reproduction of pests such as rice-feeding ear-cutting caterpillars, black cutworms, bark-boring beetles, etc. (FAO 2011)	• Studies indicate that shifting transplantation dates could increase yields by 20-27% • Awareness programmes through media platforms have been successful in educating and motivating farmers for restoration of rice landscape bio-diversity. Climate smart approaches for sustainable management of rice landscape in Vietnam is also one of the projects under consideration by FAO. (K.L. Heong 2014, Beau Damen 2018)
	Pineapple	• Salinity intrusion in Mekong river delta due to sea level rise is a major threat to pineapple cultivation in the river basin (Hung and Thoai 2017)	• Breeding and selection of salinity, drought and pest tolerant varieties of trees is being prioritised (Hung and Thoai 2017) • Range of structural and other methods to reduce damage due to salt water intrusion in Mekong river delta is being undertaken (Hung and Thoai 2017)
Cambodia	Rice	• Non-climate factors such as fertilizers, water, cultivars and soil fertility cause 40% variation to rice yields whereas climate variability influences the remaining 60% (Dek, Xuan, and Khanh 2017). • High temperatures have reduced paddy yield and forced farmers to increasingly use fertilizers, some have had to sell lands or live with debt (Yap 2017). • Increase in temperature reduces the rice yield, a supplementary increase in CO2 levels does not aid in the yield (Phetkham-pheng and Ko 2020). • Drought and flooding are common in the region which negatively affects the livelihood of farmers, thus forcing them to adapt by using seasonal varieties of rice to increase productivity (Kong et al. 2012). • Various climate models indicate that Cambodia will be severely affected by climate change, the changes in rice yield under the RCP 8.5 and RCP 4.5 baseline scenarios reduced the GDP by 8.16% and 10.57%, respectively (Kim et al. 2018). • Increase in pest infestations was one of the major perceptions of smallholder farmers as an impact of climate change, along with greater frequency of droughts and floods (Thangrak et al. 2020).	• Recent study found out that forward shifting planting dates and fertilizer application rates could be used as an effective adaptation strategy to climate variability (Wang et al. 2017). • Development of irrigation systems and good water management are recommended to improve production (Kea, Li, and Pich 2016). • Adaptation strategies involving deployment of short duration rice varieties, in conjunction with direct seeding and better N management, indicate comparable and improved production can be achieved (Poulton et al. 2016).

* No published research found on the impacts of climate change on cultivation of Okra (Pakistan), Coconut (Indonesia) and Pineapple (Indonesia)

** The list is non-exhaustive

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