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Review

A Review of Plastic Contamination Challenges and Mitigation Efforts in Cotton and Textile Milling Industries

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Abstract: Plastic contamination is a topical issue in the cotton and textile industries. These plastic contaminants come from diverse sources, including agricultural mulch films, improperly disposed plastic trash near cotton fields, and importantly, the plastic wraps used to cover cylindrical modules built by John Deere's onboard module builder harvesters. When these different plastic materials end up in the cotton lint bales, the value of the bale to the textile mills plummets significantly. To that end, there has been a concerted effort by the two major industries by this issue to find lasting solutions to the menace posed to their profitability by plastic. In this review article, the subject of plastic contamination within these industries is first put into perspective. Thereafter, the cotton value chain is subdivided into different phases from pre-cultivation to textile mills. The root causes of plastic contamination in each of the phases are then analyzed, followed by discussions of the select solutions that have been developed or are being developed in response to the challenge by the industry and researchers. Finally, from the author's perspective, brief projections for the future direction of plastic mitigation efforts within the cotton and textile industries are presented. This review is envisaged to serve as a useful reference for new hands starting their research career in cotton- and textile-related industries, as well as practicing professionals needing to keep abreast of developments in the industry.

Keywords: plastic contamination; cotton; gin; textile; round module; mitigation efforts; textile mills.

1. Introduction

Cotton (*Gossypium hirsutum L.*) is a globally important agricultural crop from which numerous products (including lint used in making yarns and fabrics, cottonseed oil used for human consumption and animal feed production, and linters used in making ice cream, toothpaste, filters, currency and securities, solid rocket propellants, etc.) are derived, see Table 1. Cotton lint is the most important economic product from cotton crop plants and the economic value of cotton lint has a strong correlation with the level of foreign matter present in the bale [1-5]. In the past decade, of notorious interest to the global cotton and textile industries is the issue of plastic extraneous matters that have been on the upward trend in the cotton supply chain, and which has been taking both financial and reputational tolls on the industries [1,4-10]. Plastic contaminants come from diverse sources—including agricultural mulch films, fertilizer bags, plastic shopping bags disposed at or air-blown to the fringes of cotton fields and picked together with seed cotton during harvesting, and cylindrical (popularly known as "round") cotton module wraps [3, 11-16]. Of these plastic contamination sources, the round module wraps of different colors are one of the biggest culprits [17], and particularly yellow, pink, and black color module wraps account for about 60-70%, 15-25%, and 5-10%, respectively, of the total plastic found in officially tracked US-produced cotton bales by USDA's AMS C&T [18].

Table 1. A summary of cotton products and their common applications. This shows the importance of cotton.

Cotton Product	Secondary/Derived Products	Common Uses
Lint and Linters	Paper	Currency, filters, and securities, coffee making, chemical analysis
	Yarns	Fabrics, clothing, tarpaulins, tents, twine
	Films	X-ray, packaging, tapes
	Cellulose Nitrate	Solid rocket propellant, fingernail polish, gunpowder
	Felts	Mattresses, upholstery, comforters, furniture
	Yarns	Textiles, clothing, sewing
	Cellulose esters & ethers	Ice creams, paint, lacquers, toothpaste
Cottonseed oil	Glycerin	Explosives and cosmetics
	Fatty acids	Tocopherols, vitamin E supplements, rubbers
	Refined oil	Margarine, salad dressing/whipped toppings, baking,
	Skin care creams	Anti-aging/-oxidant agent, anti-cancer agent
Cottonseed hulls*	Animal feed	Beef and dairy cattle feeding
	Landscaping mixture	Landscaping/gardening/nurseries mulching and amendments
	Drilling fluid additive	Loss control in drilling mud/bridging agent
	Skin care creams	Anti-aging/-oxidant agent, anti-cancer agent
	Furfural	Inks, adhesives, nematicides, plastics
Cotton meals	Fertilizer	Soil enhancement products,
	Animal feed	Fish feed, Dairy ration supplements, protein source for livestock

*Cottonseed hulls refer to the outer layer of cotton seeds which are the by-products of the cottonseed oil extraction process called dehulling. .

When these plastics end up in the final lint bales produced from commercial cotton gins, significantly higher effort is required from the textile mills to add value to the lint and produce textiles, if at all they are useful. Furthermore, contaminants, such as plastic, can lead to the downgrading of garments or fabrics or their total rejection, which may cause permanent friction among growers, ginners, and textile mills [19-20].

To this end, the global (and more importantly the US, which is the global largest exporter of cotton lint bales) cotton and textile industries have responded to this plastic contamination menace with numerous approaches focused on different stages along the cotton value chain from the fields to the textile mills [3-5, 21-23]. Starting from the cotton fields where the potential for plastic contamination starts, especially in cotton-producing countries where the adoption rate of John Deere's (Deere and Company, Moline, IL) automatic module building spindle harvesters (popularly known as "pickers") that use plastic cover to wrap seed cotton module is high (like Australia, the US, Israel, and Brazil), to the textile mills around the globe where cotton lint is turned into fine apparels that customers are glad to put their money on, no stage can be left out without guard against plastic contamination by the industries [24-26].

To date, there are little to no comprehensive documents that capture the ever-growing efforts of different individual researchers, groups, agencies, and industries at large at tackling plastic contamination efforts. All that exists are scanty, scattered, and often country-specific documents that are not easy to sift through and sometimes cumbersome to reference by new entrants and even some old hands in the sector. This gap needs to be filled with a comprehensive review of the state-of-the-art of global plastic contamination issue, and the historical and the most recent efforts being made by researchers and the two industries involved to tackle the issue which has been posing a great challenge.

Therefore, the objective of this review is to meet that need. It aims to highlight the main issues with plastic contamination within the cotton value chain and build a connection/link among the various research publications on the topic while highlighting the main technological solutions that have been invented/adopted and deployed or are still in the proposition or developmental phases but have great prospects. Some of the sensitization efforts by agricultural extensionists and different players in the cotton and textile industries are also discussed.

2. Materials and Methods

During the course of the author's work on some plastic contamination-related projects within the cotton value chain see [3], it quickly occurred to him that although the issue of plastic contamination is widely discussed and all hands are on deck by various experts within the industries affected to tackle the menace posed by plastic contamination to the competitive edge that cotton has enjoyed over synthetic and other natural fibers for many decades, there is limited comprehensive work that fully documents this issue and the numerous efforts and advances made thus far.

Adopted Approach

Hence, to fill the gap, this review adopts the following approach. First, the cotton value chain is divided into different stages according to the valorization phases, starting from the in-field pre-harvesting phase to the textile milling phase. At each of the phases, the different sources and causes of plastic contamination are discussed; and thereafter, the existing and emerging technologies and ideas that are geared towards solving this challenge are elaborated. Furthermore, the regulatory, extension services, and sensitization efforts by different entities across the world at each of the phases are narrated.

Materials

This paper's objectives are achieved by extensively consulting different print and electronic materials, journal articles, conference publications and talks, expert opinions, and directives from national and international regulatory agencies and professional bodies that are saddled with the responsibility of or interested in ensuring quality within the cotton supply chain.

Finally, based on all these past events and efforts, projections for the future trends of plastic contamination mitigation research efforts and technologies within the cotton and textile industries are made in the closing remarks.

3. Results

3.1. Plastic Contamination in the Pre-sowing, Pre-harvesting, and Harvesting Phases

3.1.1. Pre-sowing and Pre-harvesting Phases

The potential entrance of plastic into the cotton value chain starts with the management practices adopted by cotton growers. Many cotton growers use plastic films/mulch in their production management to meet the demand for early planting of full-season cotton [27]. The practice has been scientifically proven to improve seed cotton yields by as much as 295 to 430 kg (650 to 950 lbs.) with or without irrigation in different countries, and it also significantly increases the amount of cotton that can be harvested early, which prevents lint quality deterioration in the field after boll opening [27-29]. These improvements are a result of the capabilities of plastic film mulching to regulate soil temperature, defeat weed growth, reduce soil water loss, and therefore, increase cotton crop water use efficiency [30]. However, despite the proven advantages of the agricultural practice of mulching with plastic films, the resulting residual plastics in the field are recognized as a common soil pollutant that has been reported to impair soil quality in different regions of the world; and thus, cancels out the economic benefits of the practice [30-41].

Other sources of plastic contamination in cotton fields before harvesting are plastic garbage disposed close to cotton fields and/or air-blown into the edges of the cotton lots, fertilizer bags that were not properly handled during application and end up in the fields, busted irrigation plastic pipes during the season, etc. [3, 42].

Traditionally, attempts are made by many cotton growers to retrieve these plastics from their fields before harvesting seed cotton (e.g., mulching materials are removed after they have served their purpose), despite being laborious and cost-intensive work. However, it is often not possible to retrieve all the plastics because some break down into smaller fragments that evade retrieval/get buried in the soil. These plastic residuals get picked up by the automatic harvesters which are mainly of two types (spindle pickers and cotton strippers) in countries that have automated cotton harvesting; although the risk of picking them up is minimal in other countries like India, China, and African countries where mechanical harvesters have not yet penetrated the market and manual harvesting is still the norm [26, 43].

3.1.2. Harvesting and Post-harvesting Handling Phases

As discussed in the previous sub-section—*Pre-sowing and Pre-harvesting Phases*—the first risk of plastic contamination within the cotton supply chain may be traced to the pre-planting farming management practices adopted by cotton growers. Those plastic pieces that are not removed from the field before the commencement of harvesting operation with mechanical harvesters, whether strippers- or pickers-type, have a significant likelihood to progress through the value chain to become confirmed contaminants in the harvested seed-cotton module when packed with the harvested seed cotton. Depending on the type of mechanical harvester used, the amount of trash generally may be quite significant in the harvested seed cotton module. While the picker-type mechanical cotton harvesters are more selective in removing seed cotton from the pods (called "bolls"), using a set of spindles, the stripper-type mechanical harvesters are less selective/gentle in harvesting the seed cotton from cotton plant stands, and therefore, create more trash contents (including plastic mulch residues, shopping bags, etc.) in the value chain compared with picker-type harvesters [26, 44-45].

Furthermore, since the 2006 season when Case IH introduced their first *Module Express 625 cotton picker* followed by John Deere releasing their own model 7760 mechanical picker harvester during the 2008 growing season, modern mechanical cotton harvesters have been able to form/build modules on-board while harvesting is still in progress, which enhances cotton harvesting efficiency by eliminating the need for the investment in boll buggies, module builder, tractors and crew members required in the conventional module building approach [46-48]. More particularly, John Deere's model 7760 and its successors: CP690, CP770 (shown in Figure 1), and CS770 gained wide market acceptance among cotton growers because, unlike Case IH's on-board module builders, they form seed cotton into round modules that are approximately one-fourth the size of a conventional rectangular module, and research has shown that they have faster processing rate at gins compared with the other module types, produce seed cotton with improved moisture levels, and lint with higher color rating [49-50]. A unique feature of the round modules is that they are automatically covered with a specially engineered plastic material (made of linear low-density polyethylene (LLDPE) or high-density polyethylene (HDPE) or Polypropylene) that is water resistant and protects the seed cotton from the elements of weather—rain, ultraviolet (UV) radiations from the sunlight, and wind—unlike other module types that require additional labor to manually cover them up with tarpaulins or coated plastic which unfortunately may retain water from the rain because of their flat top and affect the moisture level of the stored seed cotton [50-51].

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Figure 1. A John Deere CP770 Cotton Picker.

Despite these advantages of the round module builder that made them the hallmark of modern mechanized cotton harvesting, they bring with them a new challenge to the industry—the risk of plastic contamination in the supply chain! Although the plastic module cover applied by John Deere's on-board module builder to cover harvested seed cotton has been well engineered to be tear-resistant [52], improper handling by the machine operators during harvesting and transportation from the field to the gin may still cause them to tear down and create plastic extraneous content in the seed cotton which may contaminate countless lint bales down the value chain. For example, unloading the finished round module from an on-board builder in the field where there are a lot of stalks may create punctures in the plastic covers from where numerous pieces break off and mix with the seed cotton; likewise, burs and sharp edges in module trucks could impair the integrity of the plastic module cover [53,54, 55], just as improper replacement of a run-out module wrap during harvest. Furthermore, some inferior plastic module wrap brands that are not as durable as the Tama Group's TamaWrap™ (Tama USA Inc., Dubuque, IA) which was originally designed and patented for round module covering have infiltrated the cotton industry, especially in the United States [56-58]. Given that the patent held by Tama Group on the module wrap will expire soon [59], it is expected that these inferior module wraps will become more widespread if prompt action is not taken.

On the other hand, although there is a very minimal probability of hand-picking the plastic residues and trash in the field together with manually harvested seed cotton in countries where cotton harvesting has not been automated, there are other source sources of plastic contamination that may need attention. For instance, manually picked cotton is usually dropped into some woven baskets or bags made of plastic materials, see Figure 2. With constant usage over many seasons, those bags wear and tear, and may end up as plastic foreign matter in the seed cotton.

(**a**) (**b**)

Figure 2. Manual Seed cotton harvesting: (**a**) Typical manual seed cotton harvesting and storage in woven bags during reaping, (**b**) An example mode of transporting such harvested seed cotton to the gin adapted from [51].

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3.2. Plastic Contamination in the Ginning Phase

3.2.1. Ginning Phase

By and large, some research works have shown that most of the plastic contamination risk in the cotton value chain is eliminated if harvesting and post-harvesting pre-ginning material flow activities are cautiously executed [55, 60]. However, there are still instances where plastic contamination is initiated at the cotton gin module feeder, especially when gin workers do not follow the recommended cutting techniques for the module wraps or when the plastic wraps are caught up by module feeder floor rollers and the wraps flow together with seed cotton into the module feeder.

When such an incident occurs at the module feeder, if the plastic wrap is large enough, it gets trapped on the module feeder's dispersing cylinders where it breaks up into smaller fragments if it is not promptly removed [3, 61]. Conventional gin cleaning equipment (cylinder cleaners) were not originally designed to remove plastic and research has shown that they are not effective in removing thick module wrap pieces [61]. Hence, the small pieces of plastic from module wraps that are left for too long on the module feeder dispersing cylinders mostly end up in the final lint bales, and thus, create plastic call scenarios for such bales implying financial loss to the primary producers. In [62], an estimate of a total of 15% of contamination is given to have originated from the cotton gins (both before and during ginning process).

The International Textile Manufacturers Federation (ITMF) in its most recent survey (2007-2019) released in the year 2020 [63] reported that different plastic-based contaminants are found in cotton supplied to textile mills. From the report contaminants tagged "strings made of plastic film" and "fabrics made of plastic film" each affected 39% of all evaluated cotton samples delivered to textile mills by cotton gins across the world; "strings made of woven plastic" and "fabrics made of woven plastic" affected 36% and 31%, respectively, of the cotton samples analyzed. These values

3.3. Contamination at the Textile Mills

3.3.1. Handling at Textile Mills

For many decades, the issue of contamination has been a subject of discussion in the textile industry. One of the foci is usually on having cotton value models that avoid Polypropylene (PP) or generally plastic packaging materials [62]. However, despite this focus, there has been a general uptrend in foreign matter contaminations within the global textile industry and this is not restricted to just cotton textile milling line, but it affects those that mill other fibers too [62-64].

Plastic contamination is of particular interest among other contamination types at spinning/textile mills—dead and immature fibers, threads, old pieces of fabrics, feathers, white PP, jute, etc.—because while most of these other contaminant types are either both spinnable and/or dyeable, cotton is neither spinnable nor dyeable [65]. Thus, plastic contamination is very critical to quality at textile mills.

According to an estimate by Uster® [62], only a total of about 10% of all contaminants in the cotton value chain are introduced during spinning operations (bale stocking and the actual process), compared to the 40% and 20% introduced in the pre-harvesting and harvesting phases of seed cotton, respectively. Given that plastic is only a fraction of the total contaminants, the amount of plastic contamination originating during the spinning process/textile milling may be small, however, even a small piece of plastic in fiber may result in significant cost and quality loss implications in the finished products—yarn or fabrics/garments.

The major factor contributing to the origination of contaminants at textile mills is the significant level of automation that has taken place within the textile industry globally over the past few decades [63, 66]. This is so because, while automation has brought significant improvement to the spinning and milling processes by reducing labor costs and minimizing human interventions, the replacement of humans by machines at different stages has resulted in all kinds of foreign materials that were hitherto detected and removed manually by human inspectors going undetected until after they have been torn into smaller fragments and contaminated numerous yarns, at a stage when it is late to remedy the damage because automated machines have limited capabilities to detect and eject foreign matter [63, 67].

4. Discussion

4.1. Plastic Mitigation Efforts: Pre-planting, Pre-harvesting, and Harvesting Phases

Numerous efforts have been made to control plastic contamination in the field. First, awareness is very important, and several sensitization/awareness campaigns have been made by various industry stakeholders. In the US, despite the report that the cotton industry produces one of the very cleanest cotton in the world [63], the industry regulators are leaving no stone unturned to ensure that the country maintains the high reputation of her cotton which have enjoyed premium prices in the international commodity market for many decades because of the contamination-free quality they have. For instance, free educational videos and printed materials were made by important cotton industry governing/regulating councils in the country to educate growers, and particularly machinery operators, on best practices to adopt before and during mechanical cotton harvesting [67-69]. Growers are advised to practice good housekeeping in the field and around handling equipment, check their fields and retrieve trash that may contaminate seed cotton before harvesting starts, routinely clean their cotton harvesters' heads, ensure proper replacement of run-out module wraps on the onboard module builders with industry-standard module wrap during harvesting, and in cases where conventional modules are still used for packaging seed cotton farmers are encouraged to replace torn module covers promptly and use module chords instead of plastic to tie down modules during transportation. It is recommended that round modules should be transported at least 15 cm above the ground surface to prevent damaging the underside of the module wrap. Communication between growers/harvesting crew and the gin managers is emphasized—when round modules with issues during harvesting are flagged and communicated ahead of delivery to ginners, the gin managers are better prepared to mitigate plastic contamination risk from the damaged module cover.

Furthermore, in Australia, a country which is also rated by ITMF as one of the producers of the cleanest-quality cotton globally, different efforts are also ongoing to maintain the contamination-free quality even though the issue of plastic contamination seems not to be as severe as compared to the US cotton industry which widely adopted the onboard module builder-type harvesters later than the Australians. The early adoption of the onboard module builder in Australia has ensured that most of the teething problems associated with the new technology adoption have been resolved earlier than in a country like the U.S. that is now overcoming the issue of plastic contamination that is coupled with automatic cotton harvesting and module building. The Australian response has also been aimed at implementing best management practices (BMP) during harvesting to minimize in-field contamination [70]. Asides, in Australia, there has been some research success in the development of thin biodegradable plastic films for mulching, which do not remain on the soil surface at harvest, and this may eliminate an important source of plastic contamination which enters the cotton value chain in the field when fully available for growers' use [35].

Across different countries where cotton is cultivated, there have been some research studies aimed at detecting different types of plastic trash in cotton fields using remote sensing and image processing techniques [30, 71-74]. These techniques which mostly rely on imageries taken aboard unmanned aerial vehicles (UAVs) with one or multiple multispectral camera(s) on board have shown good prospects for the detection of plastic in cotton fields at different stages of the crop physiological maturity and thus, have been proposed for in-field managing/mitigation of plastic contamination of seed cotton to create maps of plastic locations within cotton fields that can aid retrieval before harvesting [74].

4.2. Plastic Mitigation Efforts: Ginning Phase

Cotton gins have a big responsibility of ensuring that their lint bales are as clean as possible to maintain a good reputation and ensure cordial relationships with their textile industry customers. Thus, even if plastic contaminants arrive in the cotton modules from the field, it is the responsibility of the gin to ensure that they are removed without ending up in the final lint bales they produce. In the U.S., the USDA has introduced additional plastic contamination codes 71 and 72 on the permanent bale identification (PBI) system which serves as an accountability scheme for every bale produced in the US and classed by the USDA [75]. The USDA does not permit the changing of the plastic contamination classification of any bale from which samples are taken, even when new samples are sent in for review classification because the distribution of plastic foreign matter is usually non-uniformly distributed in the plastic-contaminated bale. Thus, ginners are bound to be more circumspect in the handling of seed cotton they process to reduce the possibility of having permanent a plastic code for their cotton bales which causes discounted prices for their products.

Furthermore, other research works focused on mitigating plastic contamination at the cotton gin include the development of a machine vision-based plastic detection-ejection system by researchers at the USDA-ARS Gin Lab, Lubbock (in collaboration with Bratney Companies, Des Moines, IA, USA, a leading company in industrial optical sorting and cleaning operation) which detects incoming plastic materials at the gin-stand apron and puffs them out with air produced by a set of solenoid-controlled air-knives. This system has been tested with satisfactory performance in-house at the USDA and some commercial gins during multiple seasons [76]. The success of the tested prototype has led to the production of a commercial model marketed as Visual Imaging Plastic Removal (VIPR™) by Lummus Ag Technology (Savanna, GA, USA) and Bratney Companies [77]. The reported demonstrated aggregate accuracy detection and ejection efficiency of the system is about 90%, and the system has been made available to commercial gins on a restricted basis since 2021 ginning year. Generally, the gins at which the system was pilot tested witnessed a significant decrease in the plastic calls for their bales relative to previous years.

Also, another promising research effort towards mitigating plastic contamination at cotton gins is the optical inspection system for module feeder, which was also developed at the USDA, and relies on video streams from one or numerous network IP camera(s) installed at the back wall of well-lit module feeder [78-79]. This solution shifts the plastic mitigation focus further upstream of the ginning line, relative to the VIPR™, thereby ensuring that ginners can promptly detect plastic pieces caught on the module feeder before they break into smaller fragments that require a system like the VIPR™ system to remove or end up in the final lint bales downstream. Subsequent development of this system incorporated a custom software that pauses the module feeder floor on a user-defined-frequency and captures a few still images of the module feeder (for a few seconds) which may be used to detect the presence of plastic on the module feeder [80].

Moreover, researchers at Texas A and M University who hold the paradigm that plastic contamination could be better mitigated at the gin if plastics are intercepted and eliminated earlier in the ginning line proposed, designed, and fabricated a brush-based plastic removal mechanism for installation at cotton gin module feeder [3]. The conceptualized idea is to have a brush mechanism that may be integrated with the USDA's automatic module feeder inspection system and can be automatically deployed to run against plastic pieces that are detected on any of the module feeder's dispersing cylinders and remove them by abrasive forces. The brush system has been designed, fabricated, installed on a micro gin module feeder at Texas A and M University, and optimized for maximum plastic removal efficiency based on some identified explanatory factors [81]. Efforts are still ongoing to fully integrate the optimized brush mechanism and the optical plastic sensor—the USDA's automatic module feeder inspection system—to form an optimized closed-

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loop plastic detection removal system. Successful completion of this system will ensure that

Because most of the plastic contamination events that are initiated at the ginning phase of the cotton supply chain relate to the improper handling of round module wraps, some of the educational materials produced by relevant industry agencies/regulators have emphasized the training of ginning crew on the appropriate handling/unwrapping technique of the module wrap at module feeder to prevent plastic contamination events [68, 69]. Also, to help with the appropriate unwrapping of the cylindrical module cover, Tama Group, the manufacturer of the module wrap, created a set of recommendations and guidelines for handling the modules at gins as shown in Figure 3. In addition, since the 2018 season, a cutting zone indicator (Tama Cut Indicator™) has been included on the module wraps to assist gin workers in the effective unwrapping of the plastic at gins in a manner that minimizes the risk of plastic contamination [51].

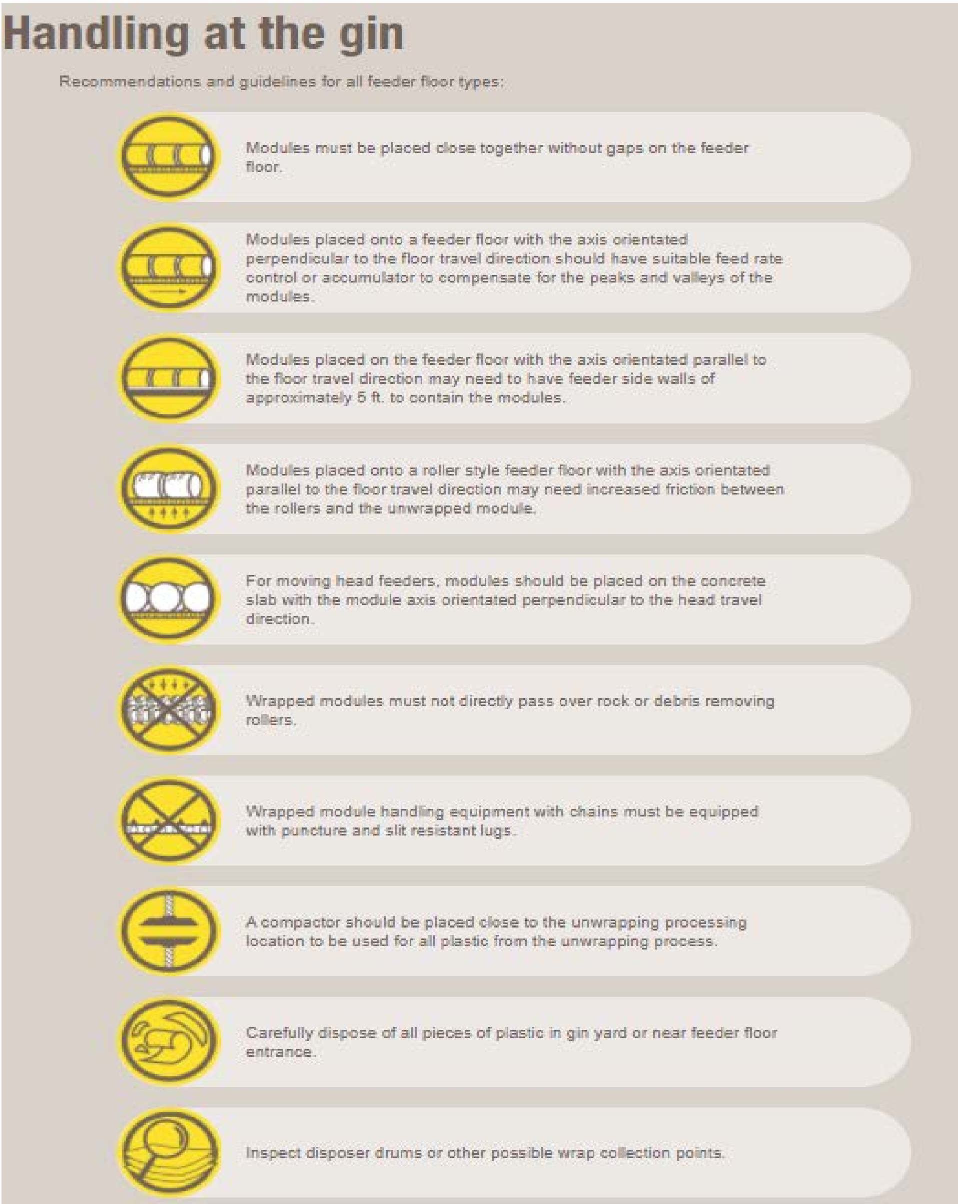

Figure 3. Manufacturer's recommendations and guidelines for handling round seed cotton modules at gins to minimize plastic contamination (adapted from [51]).

Noteworthy is the development of a seed cotton contamination and leaf cleaner, available in two models MZQ-7A and MZQ-10, by Handan GoldenLion Cotton

Machinery (Handan City, China) specifically for cleaning hand-picked seed cotton. The product is commercially available, and the manufacturer claims it can remove about 40 to 60 % trash content in seed cotton. However, this machine is not capable of removing thick plastic materials and other hard trash contents in seed cotton as confirmed by a group of researchers from the USDA and Cotton Incorporated (Cary, NC, USA) [82]. However, it may be very useful in some cotton-producing regions of the world where cotton harvesting has not been automated and the major risk of plastic contamination come from thin mulch films.

Some previous studies have also investigated the use of ion mobility spectroscopy techniques for detecting plastic contamination in seed cotton. The idea started with Gas Chromatograph-Mass Spectroscopy (GC-MS) identification of voltaic organic chemicals (VOC) that are released by typical plastic contaminants (PP, LLDPE, or HDPE) in cotton when they are subjected to an elevated temperature of around 100 °C, which is typical during ginning operation and within the tolerable recommended limit for cotton drying, and showed promising results at detecting the even small concentration of plastic matter in seed cotton [83]. In the future, this technique may serve as a useful basis for the development of a plastic sensing system that can be an alternative to the optical sensors (cameras) needed by computer vision algorithms like the VIPR and USDA's module feeder inspection systems.

4.3. Plastic Mitigation Efforts: Textile Mills

As stated earlier, the increased level of automation in the textile milling industry led to the late detection of plastics in the textile milling process. Hence for many years, the textile mills suffered significant losses because contaminants, particularly plastic trash, were not detected earlier in the textile production procedure. The first response of the industry was to blacklist cotton lint gins suppliers/regions from which contaminated lint bales were supplied. Hence, cotton growers and ginners have been stimulated to be more careful in their production and cotton module management and processing practices as discussed in the previous sub-sections. And some advancements are being made by the global cotton industry toward producing and supplying clean lint bales, devoid of plastic and other non-lint materials, to the textile industry.

Apart from blacklisting/penalizing cotton lint from some regions that have been identified to supply plastic-contaminated lint bales, some of the leading textile machinery manufacturers in the world have made efforts to create technological solutions to assist the spinning/textile mills in the detection and removal of contaminants at the different stages of spinning (blow room, carding and comber, draw frame and lappers, ring frame and winding), especially at early stages before they get shredded into fragments that degrade the quality of yarns/fabrics [84]. These solutions are divided into two broad categories: removal systems (or sorting machines) in the blow room and electronic yarn clearers that are equipped with a suitable foreign fiber channel. The removal system types are designed to handle bulk contamination with substantial sizes, while the yarn clearers are designed to eliminate small-size contaminants. It may be possible to use only yarn cleaners when the level of non-fiber contents like plastic is minimal, but not in situations where there are significant contaminants [85].

The first of these commercial solutions known as Loptex Sorter (Loptex SRL, Como, Italy), came in years ago with significant success and improvements afterward [86-87]. Loptex's system uses pneumatic valves at the beginning of the spinning process before carding machinery and can be integrated into existing and new blow room lines. The system is modular in design and has a high detection resolution and accuracy afforded by the combination of a camera/ultrasonic sensor system, multiple light sources, and bespoke software, which together detect contaminants as being darker than cotton fiber. It removes hazardous trash including plastic (PP) upon detection by activating the variable electronic control signals for the pneumatic valves, which depend on the contaminant size, to enhance the spinnability and dyeability of cotton fibers [85]. The Loptex Sorter was successful because of these special features, and this made other competing manufacturers adopt a similar approach. These other solutions including Barco Vision Cotton Sorter, Premier Fiber Eye, Uster Optiscan, and Vision Shield are installed at the blow room to detect and remove contaminants that may be detected by spectral (color) characteristics.

Uster offers some commercial contamination control technologies. For instance, installing the Uster's fiber cleaners inline at the blow room just after the opener but before carding gives spinners control over the contamination level in the carded fleece and the final product (the yarn). The Uster's Jossi Vision Shield N relies on highly sensitive imaging spectroscopy technology to rapidly detect contaminants, particularly plastics, at higher resolution (and over a large wavelength spectrum) than most other systems, including the Loptex Sorter because the fiber tufts are uncluttered at the stage of fiber processing at which it is integrated [88]. Upon detection, the contaminants are ejected similarly to the Loptex Sorter using precision valves to perfectly time every ejection of only the contaminant. The system comes in different width sizes to meet customers' specific needs.

5. Conclusions

The global textile industry is very vast, contributing about USD 1 trillion to the global economy as of 2021. This value is anticipated to grow at an annual rate of 4.0% from 2022 to 2030, based on increasing fashion trends. And given the clamor for sustainability in every sector of the global economy, cotton which is the natural fiber of choice will continue to be relevant if it can maintain its cleanliness reputation of containing minimal foreign extraneous matter content and biodegradability/recyclability.

In the coming years, it is envisaged that there would be a significant substitution of normal polyethylene (P.E.) mulching films with biodegradable plastic mulches (BDMs) which are already starting to penetrate the global agricultural markets. Adoption of such BDMs in countries like China, India, etc. where mulching is a major cultural practice in cotton agronomy and manual harvesting is still the norm will ensure the minimization of plastic contamination risk within the cotton value chain, and thus, increase the supply of more contamination cotton to the textile mills.

Furthermore, it is my opinion that the adoption rate of onboard module builder cotton harvesters will continue to increase across the world due to the machines becoming more affordable to growers in some parts of the world (Asia and Africa) where the prices of the new machine are currently prohibitive. In some years, some of the current models in the US, Australia, Brazil, Israel, and other countries where cotton harvesting has been largely automated will be sold off to growers in other climes where the prices of the new machines are unaffordable. This trend will help reduce the general trend of plastic contamination cotton value chain because the new owners of the mechanized harvesters would have a global archive of materials from which to learn plastic mitigation practices.

There would also continue to be significant efforts from cotton growers, researchers, regulatory agencies, and commercial equipment manufacturers to ensure that the systems for detection and removal/elimination of plastic (and other contaminants) across the cotton value chain from field to textile mills are continuously developed and optimized. Especially, soon, the current TamaWrap™ material may get replaced with a novel non-plastic material that will offer the same protection against the elements of weather but is easier to detect and remove from cotton processing lines.

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"The author declares no conflict of interest either financial or personal relationships that could influence the work reported herein."

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The author declares that the mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by Texas A and M University and does not imply approval of the product to the exclusion of others that may be available in lieu.

Appendix A: Not applicable.

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