THE IMPORTANCE AND DETECTION OF COTTON IDENTITY THEFT: CONCEPTS AND PROCEDURES

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Introduction

This study aimed at solving a serious problem that in recent years has resulted in major losses to the U.S. economy. This problem is cotton identity theft, represented by enormous claims that cotton textile products sold in the U.S. market and in many areas around the world are made from premium cotton varieties, with the primary target being U.S. medium/long staple cottons, and U.S. Supima Extra Long Staple cottons. In 2007 alone, the claims of U.S. Supima cotton stamped on textile products worldwide reached a record high of twice as much the actual production of this cotton type. In other words, products that were labeled “Supima cotton” far exceeded the actual production of this cotton. Marketing reasons for these false claims include:

(1) Taking advantage of many trade regulations that give advantages to U.S. cotton-made products.
(2) Selling products at higher prices using premium U.S. cotton labels and trademarks.

On the technical side, it is well known that detecting these false claims in a textile product at the initial sales point is virtually impossible. Many of these claimed products are using high-end short-staple or medium-staple cottons and many other are using blends of Supima and other low-quality cottons. Once the product is dyed and finished, it becomes impossible to detect the type of cotton used with any degree of efficiency.

In addition to the losses resulting from tarnishing the famous quality of U.S. cotton, identity theft can ultimately lead to substantial losses resulting from lower demands for U.S. cotton, legal disputes, and overall quality deterioration. Indeed, if one lists the many reasons leading to the fall of the U.S. textile and apparel industry in recent years, cotton identity theft will be among the hidden reasons.

The main objective of this study was to develop verifiable scientific approaches for identity recognition of cotton fiber varieties not only in the raw stage but also in finished end products. Although the main target is the U.S. cotton, which amounts to over 20 million bales of medium staple and nearly a million bales of Extra Long Staple fibers, this work also deal with other non-US cotton varieties such as Egyptian cotton.

This part of the study focuses on the possibilities and challenges facing detecting cotton identity theft. Obviously, the problem is far from being completely solved and the effort here represents a small step toward solving the problem but it is not sufficient to overcome this problem.

General Concepts of Fiber Identification

Fiber identification has been a part of textile studies for many years. This can be achieved using many standard tests including [Cotton Production and Consumption Statistics, 2006; Luniak, 1953; Mauersberger, 1954; Stoves, 1958]: microscopic, chemical, burning, and physical tests. Microscopic tests represent the most common technique of fiber identification and they rely on detecting surface and cross-sectional features that are unique for certain fibers. For example, a cotton fiber will have a flat or oval cross-section and convoluted shape along its axis; a wool fiber will have a round or oval cross-section and a scaly shape along its axis; some rayon will have rounded serrated cross section and grooved shape along its axis; and some silk will have a triangular cross section. When synthetic fibers are examined for fiber identification, microscopic tests become limited due to the fact that these fibers can be made in a wide variety of cross sections and longitudinal shapes even within the same fiber type. For example, some nylon fibers may be rounded in cross-section; others can exhibit a square cross-section with voids; and others may have a Trilobal cross-sectional shape. Some acrylic fibers may have a mushroom cross section and others may have dog-bone cross sectional shape.

Chemical tests rely on stimulating the polymeric substance of fibers by dissolving or coloring for the sake of identifying the type of polymer from which the fiber is made. This type of fiber identification is useful particularly when different fiber types such as cotton and polyester are blended together as it can reveal the percent of each fiber in the blend. However, the limitation of this type of identification testing becomes obvious when one attempts to use it in identifying different varieties of the same type of fiber. This limitation is best illustrated in the comparison between different cotton varieties (e.g. American Upland cotton, Supima cotton, Egyptian cotton, etc.). As will be discussed later in this section, the chemical composition of a cotton fiber is a very complex one.

The burn test is a common one as it represents a simple way to identify fibers based on their thermal behavior (burning or melting), and the fiber smell upon burning. Commonly the burn test is used to determine if the fiber is natural, manmade, or a blend of natural and manmade fibers. In other words, it is useful in narrowing the choices down to natural or manmade fibers.

This elimination process is not only useful for the sake of identification but also for giving information necessary to decide the care of the fabric. In a burn test, cotton, being a plant fiber, burns when ignited with a steady flame and smells like burning leaves. The ash left is easily crumbled. Linen will exhibit the same behavior as cotton except it will take longer time to ignite. Silk, being a protein fiber, will burn easily, not necessarily with a steady flame, and smells like burning hair. Wool is also a protein fiber but it is typically harder to ignite than silk. Again, the smell of burning wool is like burning human hair. Man-made fibers will behave in many different ways depending on the fiber type. For example, acetate is made from cellulose (wood fibers), technically cellulose acetate. As a result, it will burn readily with a flickering flame that cannot be easily extinguished. The burning cellulose drips and leaves a hard ash. The smell is similar to burning wood chips. Acrylic (acrylonitrile) is made from natural gas and petroleum. As a result, it burns readily due to the fiber content and the lofty, air filled pockets. A match or cigarette dropped on an acrylic blanket can ignite the fabric which will burn rapidly unless extinguished. The ash is hard. The smell is acrid or harsh. Nylon being a polyamide made from petroleum, will melt and then burn rapidly if the flame remains on the melted fiber. If you can keep the flame on the melting nylon, it smells like burning plastic. Polyester is a polymer produced from coal, air, water, and petroleum products. As a result, it melts and burns at the same time, the melting, burning ash can bond quickly to any surface it drips on including skin. The smoke from polyester is black with a sweetish smell. The extinguished ash is hard. Rayon is a regenerated cellulose fiber which is almost pure cellulose. Rayon burns rapidly and leaves only a slight ash. The burning smell is close to burning leaves.

Physical testing is not a common approach of fiber identification although it can be very useful. This is where values of key physical properties are used to identify fiber type and fiber contribution in a blend. Examples of physical properties used to identify fiber types include [El Mogahzy and Chewning, 2002]:

- Fiber length
- Fiber diameter
- Fiber specific gravity
- Fiber strength
- Fiber elongation

Cotton Fiber

This study primarily focuses on cotton fiber identity. For this reason, it is important to review the different aspects associated with this important fiber. Cotton fiber represents a key textile component that has been used in millions of products. The merits of using this fiber are obviously realized by the millions of users of cotton textile products representing all cultures, ages, genders, and religions. They are also realized by the numerous products in which cotton fibers are used from garments to sheets, towels to surgical drapes, and disposable to biodegradable products [El Mogahzy 2009]. This realization is a historical one. Indeed, the popularity of cotton in today's living cannot be separated from the historical evolution of cotton discovery and cotton utilization.

The structure of a mature cotton fiber may be viewed as consisting of six main parts [Morton and Hearle, 1962; El Mogahzy et al., 1998; Allen, 1993; Duckett, 1975; El Gaiar and Cusick, 1976; Seshan, 1978; Zhukov et al., 1971]. As shown in Figure 1, the first is the cuticle, or the "skin" of the fiber. This waxy and smooth layer contains pectin and proteinaceous materials. The presence of this layer has a significant impact on the smoothness and the handling of cotton during processing. However, the fact that it is a very thin layer, only a few molecules thick, makes it vulnerable to environmental effects, such as due to heavy rain and high temperature. Upon scouring, this layer is removed, which explains the increase in fiber/fiber friction.

The second part is the primary wall. This is the original thin cell wall and is mainly cellulose made up of a network of fine fibrils. The primary wall may be visualized as a sheath of spiraling fibrils where each layer spirals 20-30^{o} to the fiber axis. The thickness of this wall correlates with the extent of maturity of cotton fiber, the thicker the wall the higher the maturity. The primary wall makes for a well-organized system of continuous very fine capillaries. These fine capillaries "rob" liquids from coarse capillaries; an action that contributes greatly to a cotton material's wipe-dry performance.

The third part is called the winding layer or S1 layer. This is the first layer of secondary thickening and it differs in structure from either the primary wall or the remainder of the secondary wall. It is an open "netting" pattern of fibrils that are aligned at 40-70° angles to the fiber axis. The fourth part is the secondary wall, which consists of concentric layers of cellulose constituting the main portion of the cotton fiber (also called S2 layer). During the growth period, a new layer of cellulose is added to the secondary wall. The fibrils are deposited at angles of 70-80° with points along the length where the angles are reversed. The fibrils are packed close together, again forming small capillaries.

The fifth part is the lumen wall. This wall separates the secondary wall from the lumen, which represents the sixth part. It appears to be more resistant to certain reagents than the secondary wall layers. The lumen is a hollow canal that runs the length of the fiber. It is filled with living protoplasts during the growth period. After the fiber matures and the boll opens, the protoplast dries up and the lumen will naturally collapse.

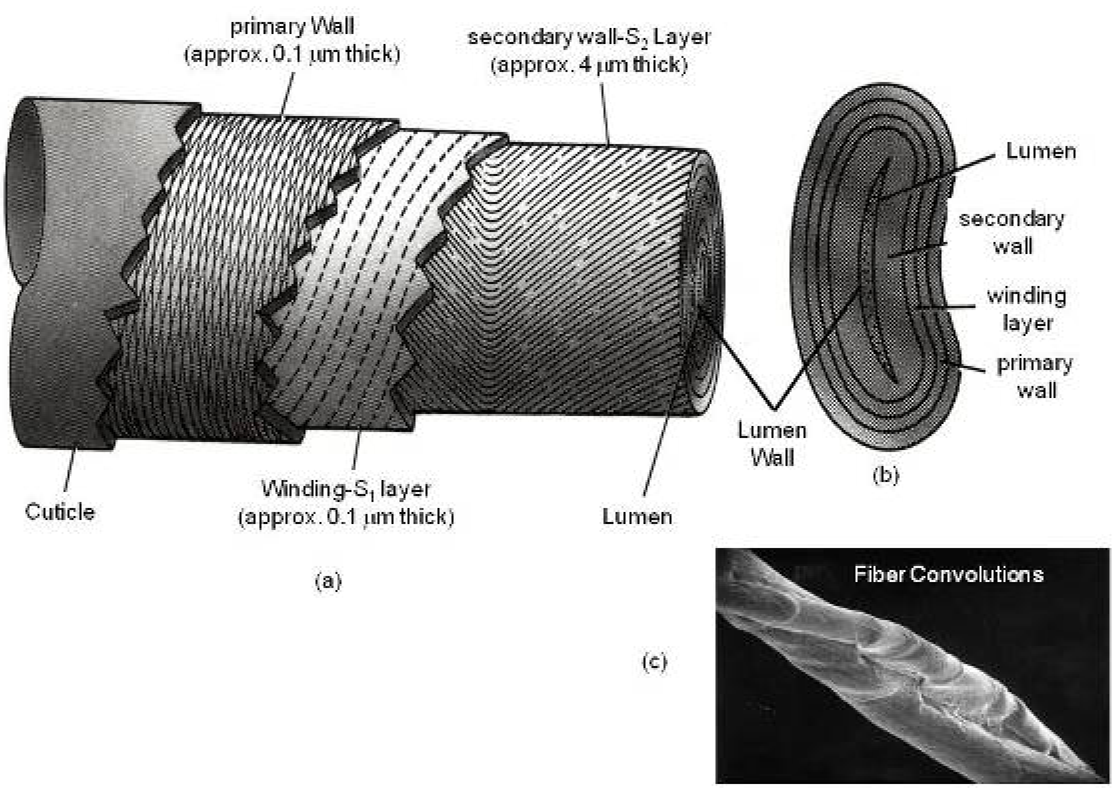

Figure 1 Structural features of cotton fiber [5]

The Importance of Detecting Cotton Identity Theft

The importance of detecting cotton fiber identity theft stems from the fact that cotton fiber has unique performance characteristics that are uncontested by other fiber types. In addition, different cotton fiber types will exhibit different performance levels. Indeed, the true value of any fiber can only be realized through the benefits of using the fiber in particular textile products. These benefits are determined by a number of performance characteristics that are primarily experienced during the use or the maintenance of the products. In order to understand how cotton compares with other competing fibers with respect to end product performance, it will be important to first define the term performance characteristic. According to Dr. Elmogahzy [2009]:

> *"Performance characteristic is hardly a direct attribute that can be imbedded in the product in a systematic fashion to make the product perform according to its expectation. Instead, it is often a function of carefully assembled elements leading to the end product, associated with a combination of different attributes that collectively result in meeting the required performance of the product assembly. In this regard, it is important that both the assembly elements and their attributes are harmonized so that their integral outcome can lead to an optimum level of the desired performance characteristics. For example, suppose that the desired performance characteristic of a fibrous end product is durability. In this case, the selection of a fiber exhibiting high strength will represent a key element/attribute combination. When the fibers are converted into a yarn, the new fiber assembly should still meet the same level of the desired performance characteristic, enhance it, or at least should not hinder it. The new element/attribute combination to be optimized in this case is yarn structure/yarn strength. Similarly, as the yarn is converted into a fabric, fabric construction/fabric strength combination should be optimized. Finally, fabric finish must be carefully selected and applied in such a way that can enhance durability, or minimize any side effects that can lead to deterioration in this critical performance characteristic."*

Perhaps, no textile performance characteristic is more important than durability. Cotton fiber is typically not the most durable fiber by comparison with other fiber types. However, in the form of a yarn or a fabric it can be truly durable. This aspect will be addressed in part 3 of this series of papers in the context of comparing the durability of different cotton fibers. In Tables 1 a comparison between the strength properties of cotton fibers and other competing fibers was made. These properties directly influence the durability of a textile product. In general, the stronger the fiber, the stronger the textile product made from this fiber. Within the different varieties of cotton, one can find a wide range of fiber strength. This point was demonstrated in Table 1 by a range of fiber strength from 3.0 to 5.0 g/denier. Typically, extra-long staple cotton fibers (ELS) exhibit significantly higher strength than medium or short-staple cotton varieties. As a result, textile products made from ELS cottons are expected to exhibit more physical durability (e.g. tensile, tear, and bursting strength) than those made from medium or short-staple cottons. Furthermore, ELS cottons exhibit longer lengths and finer diameters than medium and short-staple cottons. These two attributes contribute to the physical durability of textile products particularly when these products are made from fine yarns. Longer and finer fibers result in more fibers per yarn cross section leading to stronger yarns.

When cotton is compared to other fiber types, one will find that cotton fibers are generally stronger or equivalent in strength to all other natural fibers except long-vegetable fibers (e.g. flax or jute). Obviously, synthetic fibers can be made strong by virtue of the control of their molecular orientation, but those that are typically blended with cotton are made to have more or less equivalent strength. The breaking extension of cotton is lower than that of most competing fibers except long-vegetable fibers. The importance of this attribute is realized when a product is subjected to stretching during use. Realizing the poor extension of cotton fibers has resulted in the use of a small quantity of a companion stretchable fiber in many cotton products such as denim, bed sheets, and knit apparels. This fiber is an elastomeric fiber called spandex (trade name Lycra®). This fiber is added to provide fit and tactile comfort (stretch and recovery) to cotton textile products.

A key point related to breaking extension is that it directly influences the breaking extension of yarn. In other words, fibers of high breaking extension will result in yarns of high breaking extension. This point is critical on the ground that cotton yarns must be sized (coated by a surface film to reduce hairiness and improve abrasion resistance) before it can be woven. Unfortunately, size treatment will inevitably reduce yarn elongation, particularly when size add-on is increased. This leads to undesirable stiffness in the yarn during weaving. It is important, therefore to use fibers of high elongation so that yarns made from these fibers will likely to survive the reduction in elongation upon sizing. It is important to keep in mind that the absolute minimum value of yarn elongation below which the yarn will not weave properly is 4%.

Another key fiber attribute related to durability is fiber toughness, expressed by the so-called "work of rupture". This is a measure of the energy needed to break the fiber. In this regard, a fiber can be strong but not very tough (e.g. long-vegetable fibers such as linen). This means that although the fiber is strong, it may fail easily under excessive external stress applied in a short period of time (e.g. impact force). When cotton fibers are compared to wool fibers, one will find that cotton is significantly stronger but considerably less tough than wool. Silk on the other hand exhibits the highest toughness among natural fibers.

Stiffness is another key mechanical parameter, which influences the durability of textile products. This is determined by the initial slope of the stress-strain curve, or the so-called initial modulus; the higher the initial modulus, the higher the fiber stiffness. In practical terms, flexibility is the ease of material to deform or deflect under small forces. This may be in the tension mode or in the bending or twisting mode. The data of initial modulus shown in Table 2 is taken under tensile forces (tension mode). This data indicates that cotton fibers exhibit a wide range of flexibility (range of initial modulus from 390 to 740 g-wt/tex). This means that different cotton varieties may have different levels of flexibility. In general, cotton is more flexible than other long-staple vegetable fibers (e.g. linen and jute) and silk, and stiffer than wool fibers.

Table 1. Comparison of strength properties of different fiber types [El Mogahzy and Chewning, 2002, El Mogahzy, 2009]

Fiber type	**Tenacity-dry (g/denier)**	**Tenacity-wet (g/denier)**	**Breaking extension (%)**
Cotton	3.0-5.0	3.3-6.0	5.0-7.2
Linen	5.5-6.5	6.0-7.2	2.5-3.5
Rayon (Regular tenacity)	0.73-3.2	0.7-1.8	15.0-30.0
Rayon (High-modulus)	2.5-5.5	1.8-4.0	5.0-15.0
Acetate	1.2-1.4	0.8-1.0	20.0-25.0
Triacetate	1.1-1.3	0.8-1.0	20.0-25.0
Wool	1.0-1.7	0.8-1.6	30.0-45.0
Silk	2.4-5.1	1.8-4.2	20.0-25.0
Nylon (regular tenacity)	3.0-6.0	2.6-5.4	20.0-30.0
Polyester (Regular)filament	4.0-5.0	4.0-5.0	20.0-30.0
Polyester (High-tenacity) filament	6.2-9.4	6.3-9.5	6.0-10.0
Polyester (Regular)-staple	2.5-5.0	2.5-5.0	20.0-30.0
Polyester (High-tenacity)-staple	5.0-6.5	5.0-6.4	20.0-25.0
Acrylic	2.0-3.5	1.8-3.3	15.0-25.0
Modacrylic	2.0-3.5	2.0-3.5	10.0-15.0
Polypropylene	4.8-7.0	4.8-7.0	20.0-30.0
Spandex	0.6-0.9	0.6-0.9	500-600

Table 2. Non-standard mechanical fiber properties [El Mogahzy, 2009]

Fiber type	Work of rupture (g/tex)	Initial modulus (g/tex)
Cotton	0.52-1.52	390-740
Linen	0.82	1830.00
Rayon (Regular tenacity)	3.12	486.00
Rayon (High-modulus)	1.5-2.0	700-1000
Acetate	2.20	370.00
Wool	2.7-3.8	215-310
Silk	6.00	750.00
Nylon (regular tenacity)	7.75	270.00
Polyester (Regular)-Filament	5.40	1080.00
Polyester (High-tenacity)-filament	2.20	1350.00
Polyester (Regular)- staple	12.00	900.00
Acrylic	4.80	630.00

Durability of textile products can also be measured using parameters that are related to exposure of material to certain environments or chemical treatments during processing or during use. Table 3 provides comparison between different fiber types using some of these parameters. Under prolonged exposure of sunlight, most natural fibers will suffer some form of deterioration either via strength loss or coloration. Cotton fibers are highly resistant to sunlight provided that no rain or wetting condition is involved. Some studies found a slight loss of fiber strength under prolonged exposure of sunlight. The behaviors of other fibers are illustrated in Table 3. Abrasion is a form of rubbing against fiber surface at high speeds that can result in wearing out the fibers. Under abrasion effects, cotton fibers generally perform well. These effects begin during harvesting and continue during ginning and textile manufacturing. During weaving cotton yarns are subjected to excessive abrasion effects and at high speeds, which requires additional protection to yarn surfaces via sizing. Most natural fibers exhibit fair to good abrasion resistance, but silk in particular is known to have poor abrasion resistance. Most synthetic fibers are spin-finished in such a way that allows high abrasion resistance. Unlike long-vegetable fibers, cotton fibers require special care when treated with acid or alkalis during finishing or during washing.

Table 3. Other durability parameters of fibers [El Mogahzy, 2009]

Fiber type	Exposure-to-sunlight resistance	Abrasion resistance	Acid resistance	Alkalis resistance
Cotton	Strength loss	Good	Poor	Poor
Linen	Strength loss	Fair	Excellent	Excellent
Rayon (Regular tenacity)	Strength loss	Fair	Poor	Poor
Rayon (High-modulus)	Some strength loss	Fair	Poor	Excellent
Acetate	Some strength loss	Fair	Poor	Strength loss
Triacetate	Moderate	Fair	Poor	Strength loss
Wool	Yellows-strength loss	Good	Moderate	Very poor
Silk	Yellows-degrades	Poor	Poor	Very poor
Nylon (regular tenacity)	Degrades	Good to Excellent	Degrades	Degrades
Polyester(Regular)-filament	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Polyester (High-tenacity)-filament	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Polyester (Regular)-staple	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Polyester (High-tenacity)-staple	Good (if glass protected)	Good to Excellent	Good to weak	Fair to strong
Acrylic	Excellent	Fair to Good	Good except nitric	Good (to weak alkali)
Modacrylic	Excellent	Fair to Good	Good	Good
Polypropylene	Slow strength loss	Fair	Excellent	Excellent
Spandex	High resistant but it yellows	Poor	Good	Fair

Challenges of Identifying Different Cotton Fiber Types

The main objective of this study is to develop ways to identify certain variety or cotton type in a raw form or in a textile product. The key challenge associated with this objective is that the methods of fiber identification discussed earlier (microscopic, chemical, and burn tests) seem to fail to distinguish between different types of cotton fibers. Microscopically, most cotton fibers have common features that are not unique to any particular type. As a result, different cotton types may reveal microscopic pictures that are not different enough to segregate them or identify one type from another.

Chemical testing is even more challenging. Upon ginning and cleaning, raw cotton fiber is approximately 95% cellulose [Stoves, 1958; El Mogahzy and Chewning, 2002; El Mogahzy, 2009; Morton and Hearle, 1962; El Mogahzy et al., 1998]; yet some cotton fibers may have as little as 85% cellulose and others may have as much as 96% depending on the growth rate and the environment in which cotton is planted. Unfortunately, this data does not represent unique identification as this wide range of cellulose content can indeed exist in one type of cotton. A cotton fiber also has protein with a typical value of 1.3 (%N x 6.25) but it may range from 1.1 to 1.9 even within the same type of cotton. Other chemicals presented in cotton include: Pectic substances (typical = 0.9%, range 0.7-1.2), Ash (typical = 1.2%, range 0.7-1.6), natural wax (typical = 0.6%, range 0.4-1.0), Total sugars (typical = 0.3%, range 0.1-1.0), organic acids (typical = 0.8%, range 0.5-1.0). Again, any one of these components can exist over the entire range in the same type of cotton, making it difficult to identify certain cotton types based on the value of chemical composition. Most of the non-cellulosic constituents of the fiber are located principally in the cuticle, in the primary cell wall, and in the lumen.

In the context of fiber identification, it is well known that cotton fibers that have a high ratio of surface area to linear density generally exhibit a relatively higher non-cellulosic content. However, this point is difficult to study unless a huge amount of samples representing different cotton types are available. This was not possible in this study because of the limited samples and the time that could have been taken to test. In addition, within the same cotton type, one can find a substantial range of surface area/linear density ratio, making it difficult to detect on that basis.

It should also be pointed out that variations in non-cellulosic constituents (proteins, amino acids, other nitrogen-containing compounds, wax, pectic substances, organic acids, sugars, inorganic salts, and very small amount of pigments) often arise due to differences in fiber maturity, variety of cotton, and environmental conditions (soils, climate, farming practice, etc.). Thus, an identification by extraction and weighing these non-cellulosic constituents will be subject to a great deal of inconsistency. The non-cellulosic materials are typically removed by selective solvents. The wax constituent can be removed selectively with nonpolar solvents, such as hexane and chloroform, or nonselectively by heating in a 1% sodium hydroxide solution. Hot nonpolar solvents and other water-immiscible organic solvents remove wax but no other impurity, hot ethanol removes wax, sugar, and some ash-producing material but no protein or pectin, and water removes inorganic salts (metals), sugar, amino acids and low-molecular-weight peptides, and proteins. Most of the non-polymeric constituents including sugars, amino acids, organic acids, and inorganic salts may be removed with water. The remaining pectins and high-molecular-weight proteins are removed by heating in a 1% sodium hydroxide solution or by appropriate enzyme treatments. All of the non-cellulosic materials are removed almost completely by boiling the fiber in hot, dilute, aqueous sodium hydroxide (scouring or kier boiling), then washing thoroughly with water. The nitrogen-containing compounds, which constitute the largest percentage of non-cellulosics when expressed as percent protein (1.1-1.9%) largely occurs in the lumen of the fiber, most likely as protoplasmic residue, although a small portion is also extracted from the primary wall [El Moghazy, 2009]. The nitrogen-containing compounds located in the lumen may be removed using water, while those located in the primary cell wall are removed by heating in a 1% sodium hydroxide solution) a mild alkali scour such as that used to prepare cotton fabrics for dyeing and finishing).

In light of the above discussion, it follows that cotton fiber identification to detect different cotton types truly represent a challenge that has to be overcome to prevent identity theft.

In recent years, some attempts to identify cotton types were developed with limited success but great potential for further development. One of these attempts is the so-called "cotton DNA". The idea is to determine genetic roots that can identify different cotton types by developing rapid and simple method to measure expression of a gene of interest in the cotton fiber cell. This type of research was not primarily aimed at identifying cotton types but rather at the evaluation of the phenotype of genes of interest, which is useful in designing transgenic plants with desired characteristics. This type of agricultural research may have good future impacts on cotton identification particularly in the raw form. Cotton is a plant of great commercial importance. One significant product from cotton plants, cotton fiber tissue, is used in the production of textiles. The cotton fiber cells that make up cotton fiber tissue are therefore of great interest. Manipulation of the cotton fiber cell phenotype can produce novel and economically important improvements to cotton fiber tissue and, thus, to textiles. The complexity of cotton fiber development suggests that large numbers of plant genes are involved, especially during initiation, elongation and maturation. However, only about 40 such genes have been reported to date. Searching for these genes can open ideas for cotton fiber identification, a subject that is still under investigation [Ausubel et al., 1987; Dabo et al., 1993; Dellaporta et al., 1983; Katterman and Shattuck, 1983].

Fiber Identity Detection Procedures in this Study

In this study, cotton fiber identity was detected using a complete profiling approach that begins with the end-product (apparel, and bed sheets) and ends with the fiber extracted from the product. The reason for this approach is that the problem of cotton fiber identity theft is commonly discovered in the end-product where it is very difficult to confirm this theft given the different mechanical operations and chemical treatments that a fiber is subject to during spinning, weaving, and dyeing and finishing. Most testing techniques used were standard but few were developed in this study particularly on the raw fibers. Part II and III of this study discuss these approaches in depth.

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