Cotton contamination detection and classification using hyperspectral fluorescence imaging

Adnan Mustafic, Yu Jiang and Changying Li

Abstract
The presence of foreign matter in ginned cotton lowers the quality and ultimately the monetary value of cotton. Previous studies have shown benefits of using ultraviolet excited fluorescence to detect certain cotton contamination that is difficult to detect using other methods. The overall goal of this study was to explore the feasibility of using hyperspectral fluorescence imaging as a complementary tool for foreign matter differentiation. The mean spectra of lint and seven types of foreign matter were extracted from the hyperspectral fluorescence images using a region-of-interest-based approach. The principal component analysis was applied to select the optimal features from a total of 113 wavelengths covering the spectral range of 425–700 nm. The linear discriminant analysis with the selected wavelengths achieved an average classification rate of 90% for all samples. Therefore, this imaging method could be used as a complementary sensing modality to current instruments that are employed for cotton quality assessment in the textile industry.

Keywords
cotton, foreign matter, lint, fluorescence, ultraviolet, hyperspectral imaging

Cotton is an economically important crop grown primarily for the production of apparel and furnishings. During harvesting, cotton lint could be contaminated by various types of foreign matter. Foreign matter in this paper refers to non-lint materials in cotton and originates either from botanical or non-botanical sources. Botanical foreign matter typically comes from different parts of the cotton plant or other vegetation, while non-botanical foreign matter is brought to cotton fields from elsewhere. To ascertain the market value of the harvested cotton, a series of quality assessment steps are undertaken once the cotton passes through the ginning process. During ginning, most foreign matter is removed, but some remnants remain mixed with the lint fibers.

The presence of non-lint matter in ginned cotton is one of the criteria considered when ascertaining cotton quality. In the USA, samples of ginned cotton are sent to the cotton classing offices for evaluation by human classers and instrument testing. Qualified US Department of Agriculture (USDA) Agricultural Marketing Service (AMS) human classers visually examine the cotton samples and compare them to the Universal Cotton Standards for manual determination of leaf grade and extraneous matter. An instrument with the capability to quantify the amount of foreign matter in ginned cotton is the Standardized Instrument Testing of Cotton (SITC). The SITC acquires color images of the sample surface, and computes the area covered with foreign matter. Compared with the instrumental test, the determination provided by human classers is subjective and not repeatable. Recently, the USDA AMS revised the cotton classification protocol for determining cotton leaf grade by replacing the classers’ leaf determination with instrumental leaf measurement from the SITC system. Nonetheless, the SITC system does not have the ability to differentiate the type of foreign matter.

To address the issue of foreign matter detection and differentiation, various spectroscopic methods have been used. Among these methods, hyperspectral fluorescence imaging has shown promise in detecting and classifying foreign matter in cotton. In this study, hyperspectral fluorescence images were acquired from ginned cotton samples containing various types of foreign matter. The mean spectra of lint and each type of foreign matter were extracted from the hyperspectral images using a region-of-interest-based approach. Principal component analysis was then applied to select the optimal features from the spectral data. Linear discriminant analysis was used to classify the samples based on the selected features.

The results of this study show that hyperspectral fluorescence imaging can effectively detect and classify foreign matter in ginned cotton. This imaging method could be used as a complementary sensing modality to current instruments employed for cotton quality assessment. The ability to differentiate between different types of foreign matter has significant implications for the textile industry, as it allows for more accurate and reliable quality assessment of cotton.

College of Engineering, University of Georgia, USA

Corresponding author:
Changying Li, College of Engineering, University of Georgia, 712F Boyd Graduate Studies Research Center, Athens, GA 30602, USA.
Email: cyli@uga.edu
been utilized. These methods explored the spectral range of near-infrared (NIR),\(^1\) mid-infrared (MIR),\(^2\) and infrared (IR).\(^3\) Although they achieved classification rates of more than 90% for certain foreign matter (e.g., leaf, paper), a major limitation was that the spectra of samples could vary due to sample preparation. A study of using Fourier transform (FT) spectroscopy was conducted to measure the absorbance of botanical foreign matter from several different cultivars.\(^4\) The results showed that the measured spectra varied when the sample size was reduced or the sample was heated. In addition, the spectroscopic method does not provide spatial information of the samples.

Compared with spectroscopic methods, the imaging method does not require complicated sample preparation and, more importantly, it provides the spatial information about a sample. For example, the color imaging technique was used to extract \(L^*a^*b^*\) color model features for classifying four types of foreign matter, including bark, leaf, and seed coat (inner and outer).\(^5\) Extracted features were used for classification with three methods, sum of square, fuzzy classification, and neural networks. The lowest classification rate was achieved for leaf (83%) by using the method of “sum of squares”, and the performance was dramatically improved by using the method of neural networks (95%). However, these systems were not able to classify foreign matter with a similar appearance. For instance, transparent plastics or white paper cannot be correctly classified from lint using color features.

To take advantage of both spectroscopy and imaging modalities, the hyperspectral imaging technique has been proposed, which can simultaneously provide both spectral and spatial information of a sample. However, only two studies have been conducted so far to use this modality for classifying foreign matter.\(^6,7\) One study presented the system design and capability of using hyperspectral reflectance imaging in the visible and near-infrared (Vis-NIR) range to discriminate lint and 15 types of foreign matter usually found in US cotton.\(^6\) Although the study did not conduct classification, lint and transparent plastics could be misclassified to each other due to their similar spectra. Another study with hyperspectral reflectance imaging in the Vis-NIR range attempted to classify several types of non-botanical foreign matter usually found in cotton harvested in China, including human and animal hair, plastics, and polypropylene fiber.\(^7\) Foreign matter was imaged on top of lint while being exposed to light from halogen lamps. The overall classification rate was 73% and 75%, depending on whether the training or the testing dataset was used. However, the classification rates of transparent plastics were less than 50%. Thus, in addition to hyperspectral reflectance imaging, other techniques have to be considered to classify certain cotton contamination, such as transparent plastics. Plastic materials can have the most detrimental effect on the quality of the textile products, not only adversely affecting spinning performance, but also showing up as faults in the textile production, especially after dyeing.\(^8\)

An alternative approach is fluorescence imaging. Fluorescence spectroscopy was applied to analyze six types of botanical foreign matter (bract, seed coat, stem, shale, hull, leaf).\(^9\) Mixtures of foreign matter with different levels of presence were dissolved in a strong solvent. Data were analyzed with partial least square (PLS) regression, and high correlation (>90%) was found for two types of foreign matter (leaf and hull). In addition, studies were also conducted to explore the fluorescence technique for detection of non-botanical foreign matter. A total of five categories of non-botanical foreign matter (red bundle strip, black, white woven strip, white bundle strip, and white paper strip) were examined.\(^10\) All foreign matter categories were subject to fluorescence spectroscopy analysis in the UV excitation range of 320–400 nm. The results indicated the presence of photoexcitable fluorophores, which emitted in the spectral range from 420 to 600 nm. A comprehensive study using fluorescence spectroscopy was conducted to explore the optimal fluorescence emission wavelengths of both botanical and non-botanical foreign matter.\(^11\) A total of 12 types of foreign matter found in the US cotton showed obvious fluorescent emission under blue and UV excitation. The optimal emission wavelengths of the 12 types of foreign matter ranged from 320 to 700 nm. Based on these findings, the authors developed a fluorescence imaging system to classify the foreign matter using features extracted from the fluorescence images.\(^12\) The system achieved a classification rate of 80% or higher for most types but less than 70% for twine and the inner and outer part of the seed coat. The system only detected fluorescence emission from three fixed channels (blue, green, and red), which may miss the fluorescence at other wavelengths.

To address this issue, hyperspectral fluorescence imaging has been proposed to provide fluorescence information at different wavelengths. Since fluorescence emissions at different wavelengths were related to certain chemical compositions of the sample while not being affected by the color or transparent appearance of the sample, the hyperspectral fluorescence imaging has been widely applied in quality and safety assessment of agricultural products, such as differentiation of pulp and shells from black walnuts,\(^13\) estimation of apple quality and maturity,\(^14,15\) recognition of cracks in tomatoes,\(^16\) and detection of non-pathogenic bacterial cultures.\(^17\) As the previous studies have already shown that certain types of foreign matter had fluorescence emissions at...
the spectral range from 320 to 700 nm, hyperspectral fluorescence imaging could be a promising tool to detect and differentiate foreign matter.

The main goal of this study was to examine the applicability of hyperspectral fluorescence imaging to foreign matter detection and classification in the spectral range from 425 to 700 nm. To achieve the goal, specific objectives were to:

1. develop a hyperspectral fluorescence imaging system and acquire hyperspectral fluorescence images of seven types of foreign matter under the UV excitation light;
2. extract mean spectra from each foreign matter type as well as lint, and select optimal wavelengths from the spectra;
3. classify the seven categories of foreign matter and lint using the linear discriminant analysis (LDA).

**Materials and methods**

**Sample preparation**

Based on the results of a previous study, a total of seven categories of foreign matter optimally excited under UV light were used in the current research (Figure 1). The selected foreign matter included four categories of non-botanical origin (paper, plastic bag, plastic packaging, and twine) and three categories of botanical origin (inner part of seed coat (SCI), outer part of seed coat (SCO), and seed). All of the non-botanical foreign matter was obtained from local stores, with the exception of plastic packaging, which was obtained from a cotton gin (UGA Cotton Micro Gin, Tifton, GA). Botanical foreign matter was extracted from seed cotton harvested during the summer of 2014 from three cultivars (PhytoGen 339, Delta Pine 1050, and NextGen 5315). Seed coat has two distinct appearances, the dark inner part and the bright outer part due to the attached shorter lint fibers, also known as linters. Due to the distinction, it was necessary to separate it into two categories, the inner part of the seed coat and the outer part of the seed coat. Lint samples with thickness of 10–15 mm were collected from ginned cotton. An effort was made to remove as many of the smaller particles of foreign matter as possible. Prior to imaging, paper, plastic bag, and plastic bale packaging were cut into small pieces of ~1 cm²; twine was cut into small pieces with length of 1–1.5 cm; seed and seed coat inner and outer were kept in their natural size of 0.5–0.8 cm².

A total of 24 replicates were prepared for each type of foreign matter sample. The cultivar of lint was considered because the lint color of three cultivars was slightly different and it might affect the spectra. Therefore, eight lint web samples were prepared from each of three cultivars, making a total of 24 lint web samples. Each replicate of the seven types of foreign matter samples was placed on top of each lint web sample and they were imaged once. As a result, a total of 24 images from 24 replicates of samples were acquired for further analysis.

**Line scan-based hyperspectral fluorescence imaging system**

The imaging system consisted of a charge-coupled device (CCD) camera (ICL-B1410, Imperx Inc., Boca Raton, FL), a spectrograph (ImSpector V10E, Spectral

![Figure 1. Foreign matter categories used in the study. Botanical foreign matter included seed, seed coat inner, and seed coat outer, and non-botanical foreign matter included paper, plastic bag, plastic packaging, and twine.](image-url)
Imaging Ltd, Oulu, Finland) equipped with a C-mount zoom lens (XNP 14/17-0503B, Schneider Optics, Hauppage, NY), and an excitation illumination source (Figure 2). The spectrograph covers the spectral range from 400 to 1000 nm. Illumination light was provided by two UV-A Lamps (XX-15 A, Spectronics Corp., Westbury, NY) at a peak intensity of 365 nm. To separate the excitation light from the induced fluorescence emission in samples under observation, a 400 nm longpass filter (Thorlabs Inc., Newton, NJ) was attached to the lens, thus allowing wavelengths longer than 400 nm to pass, while excluding pseudo-fluorescence. The entire imaging system was contained in a black chamber, so that the ambient light would not interfere with measurements.

Hyperspectral images were captured using the Camera Link interface through a frame grabber (NI PCI-1426, National Instruments, Austin, TX) connected to a personal computer running a custom-designed image acquisition software (LabVIEW, National Instruments, Austin, TX).

Image acquisition and analysis

Samples of foreign matter on top of lint were placed on a holder attached to a linear slider (MS33, Thompson Industries Inc., Radford, VA) whose movement was controlled with a stepper motor (MDRive 23+, Schneider Electric Motion USA, Marlborough, CT). The 14-bit images with 1392 x 1040 resolution were binned 4X to reduce the spectral dimension, and saved in grayscale format. Under the UV excitation, the effective emission range of each image contained 113 wavelengths ranging from 425 to 700 nm (Figure 3). The x- and y-axes represent the spatial dimension of an image and the λ-axis represents the spectral dimension. Because the spectral resolution of the hyperspectral fluorescence imaging system was 2.8 nm, the wavelengths were presented without decimals.

To extract mean fluorescence emission from the respective wavelength, regions of interest (ROIs) were drawn using grayscale images at 582 nm from each of the foreign matter categories and lint. Since the size of foreign matter varied, the ROIs covered the whole area of individual samples. In the case of lint, four ROIs (50 x 50 pixels) were drawn on the lint area of each image from top to bottom, and the spectra of the ROIs were averaged in order to more accurately represent the lint spectrum.

Principal component analysis and feature selection

To reduce the dimensionality of the data, the principal component analysis (PCA) algorithm (MATLAB R2014a, MathWorks Inc, Natick, MA) was applied to the mean fluorescence emission from the full dataset of 113 wavelengths. Uncorrelated principal components (PCs) are formed by creating an orthogonal eigenvalues matrix through linear transformations of the original data, while minimizing the loss of

Figure 2. Schematic of the hyperspectral fluorescence imaging system. Samples of foreign matter were placed on top of a layer of cotton lint in a holder attached to a linear slider. Two ultraviolet (UV) sources induced fluorescence in samples, while the longpass filter excluded pseudo-fluorescence from the acquired images.
Concurrently, the issue of multicollinearity is avoided. Multicollinearity negatively affects the linear model by increasing its instability. Associated eigenvalues explain the amount of variation contributed by individual PCs, with the first PC contributing most variance, and decreasing subsequently. The relationship between individual observations is explained by PC scores that are in turn associated with original features via PC loadings. PC loadings with a higher magnitude indicate greater variance contribution by a particular feature, and the loading sign determines whether the contribution is positive or negative correlation. For each of the top three PCs, eight wavelengths with the most contribution were selected. If the loadings were all positive or negative, all eight wavelengths were selected from that side; otherwise four wavelengths were selected from each side. The number of selected wavelengths from each PC was an arbitrary value, and optical wavelengths could be selected using other algorithms.

Multivariate analysis of variance

The multivariate analysis of variance (MANOVA) test with respect to seven categories of foreign matter and lint under analysis was performed in SAS (PROC GLM, v9.2, SAS Institute, Cary, NC). The MANOVA was used to test the significant difference between multivariate means of different linear combinations forming dependent variables. The probability of identifying two random means from the same sampling distribution is described by the Hotelling–Lawley statistic, and the statistical significance level was set at $\alpha = 0.05$.

Classification model

The LDA model was used for classification of seven categories of foreign matter and lint. The purpose of using the LDA (MATLAB R2014a, MathWorks Inc., Natick, MA) was to classify observations into mutually exclusive classes by using the mean spectra extracted from the hyperspectral fluorescence images. The LDA uses selected wavelengths as features to create linear models that can separate classes while preserving the needed information. By implementing this approach, it is possible to maximize the variance between classes and to minimize the variance within classes.

The entire data were divided into training and testing sets, each consisting of 12 replicates. The final classification result of individual classifiers was calculated by two-fold cross-validation.

Results and discussion

Spectral characteristics of foreign matter and lint

For the seven categories of foreign matter, their spectral images showed certain trends that were dependent on the wavelength at which the images were acquired (Figure 4). Paper showed the strongest fluorescent emission at shorter wavelengths (435 nm), and gradually diminished at longer wavelengths (530, 547, and 582 nm). It was noticed that the contrast for the plastic

Figure 3. Image processing steps illustrating region-of-interest (ROI) selection and spectra extraction. The original dataset consisted of 113 wavelengths ranging from 425 to 700 nm. Mean fluorescence emission was extracted from ROIs (blue area) drawn to outline each of the foreign matter categories and lint, respectively. In this study, an image contained 113 wavelengths so that the subscript $n$ was 113. (Color online only.)
The plastic bag was opaque in appearance at 435 nm, but for wavelengths in the green spectral region (530–582 nm), the contrast was improved dramatically. The remaining five categories of foreign matter (plastic packaging, seed, SCI, SCO, twine) were darker in appearance and did not show as many variations across the entire wavelength range.

The mean spectra of the seven categories of foreign matter and lint covered most of the visible light spectral range (425–700 nm) (Figure 5). From the respective plots, several different trends can be observed. Paper exhibited the strongest fluorescence emission unlike other foreign matter categories, and was especially strong in the blue and green spectral region, but decreased substantially at longer wavelengths in the red spectral region (Figure 5(a)). Because paper is made out of processed wood pulp, in order to alter its color strong chemicals like fluorescent whitening agents

![Fluorescence images at four wavelengths of foreign matter placed on top of lint. Paper emitted much stronger fluorescence than others.](image-url)
are used. Therefore, paper has substantially higher fluorescence emission than other foreign matter.

Compared with paper, lint and other types of foreign matter showed fairly low fluorescence emission (Figure 5(b)). Plastic bags and plastic packaging exhibited fluorescence due to the addition of coloring pigments added during their respective syntheses, principally if excited with the UV light.\textsuperscript{19} The trend of increasing fluorescence emission started in the blue spectral region, peaked at 435 nm, and continued to increase in the green and red spectral range. A large number of chemical compounds that were present in different parts of the plant (SCI, SCO, seed, lint), or made out of plant (twine is made out of jute fibers) fluoresced blue and green (400–570 nm) under UV light excitation.\textsuperscript{20–22} Fluorescence emission in the red spectral range is more complex. In plant parts, the major contributor to red fluorescence comes from a group of fluorophores that belong to anthocyanin pigments, and to a lesser extent carotenoids.\textsuperscript{23,24}

**Data visualization using PCA**

Since the fluorescence emission of paper was significantly higher than that of others, the PCA was performed twice for the purpose of data visualization. The PCA was first applied to the whole dataset, and then the data of paper were removed and the PCA was again applied to the remaining data. A cluster was considered as unique when the entire cluster was clearly separated from other clusters, or the center of the cluster was separated from others with limited overlap with other clusters.

Paper formed a clearly unique cluster in the first PC space (Figure 6(a)), and four types of samples formed separate clusters in the second PC space, including lint, plastic bag, plastic bale packaging, and seed coat inner (Figure 6(b)). This led to the potential of using the system to detect foreign matter from lint, as well as to classify the four foreign matters from other types. For the remaining three foreign matters (seed coat outer, seed, and twine), twine formed its own cluster and was surrounded by seed coat outer and seed when the other foreign matter were removed (Figure 6(c)). Seed coat outer and seed could be misclassified as each other due to their overlap in the PCA score plot.

**Selection of optimal wavelengths for classification**

The optimal wavelengths should be related to all types of samples, and therefore the PCs calculated by the first PCA that was performed on the whole dataset were used for the purpose of feature selection.

Since the top three PCs accounted for 99.98% of the overall model variability, their respective loadings (PCA weighting coefficients) were used for wavelength selection (Figure 7). The wavelengths associated with higher values of the specific PCs were chosen to be considered as optimal wavelengths. The redundant wavelengths can be removed by focusing a smaller
number of selected wavelengths while avoiding a significant loss of information. A total of 24 wavelengths (eight from each of the top three PCs) were selected, and after removing the overlapping wavelengths that were repeatedly selected by different PCs, 19 wavelengths were used as optimal features for classification.

The 19 wavelengths can be categorized into four spectral ranges: violet, blue, green, and red. The violet range contained 430, 433, 437, and 440 nm, the blue range contained 464, 466, 469, 471, 474, 476, 479, and 481 nm, the green range contained 520, 522, 525, 544, 547, and 559 nm, and the red range contained 611 nm. They were closely correlated with the optimal wavelengths presented in the previous study. Therefore, the 19 wavelengths provided the most relevant information regarding the properties of the samples, which could be used for future studies or applications.

Additional multivariate data analysis was performed by using the 19 selected wavelengths as independent components of the multivariate analysis of variance (MANOVA) model and their contribution to their respective classes. The statistical test showed that all types of samples were significantly different from each other.

**Classification results**

The LDA with the selected wavelengths achieved an average classification rate of 90%. For lint, the classification rate was 96%, indicating a high accuracy of detecting foreign matter from lint. It is important for

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**Figure 6.** Three-dimensional score plots from the top three PCs for: (a) all foreign matter categories and lint; (b) dataset removing paper; (c) seed coat outer, seed, and twine.
classification of foreign matter, because any failure of detecting foreign matter would certainly result in misclassification. The high accuracy of detecting foreign matter showed the potential of using the presented system for classification of foreign matter. In addition, the lint samples from different cultivars were correctly classified as lint rather than other types of foreign matter, indicating that the proposed method was not sensitive to the superficial color of samples. Indeed, the hyperspectral fluorescence imaging is based on the amount and type of fluorophores in samples rather than their color. This is an advantage of this technique for industrial applications.

For foreign matter, the highest classification rate achieved by the LDA was for paper and twine at 100% (Table 1). Rates of at least 90% were obtained for three types of foreign matter, including plastic bags, plastic packaging, and seed coat (inner). This classification result also matched the observations from the PCA score plot (Figure 6). Both seed coat outer and seed were classified correctly 71% of the time. Seed coat outer and seed were misclassified as each other due to their similar fluorescence spectra. It is noteworthy that the hyperspectral fluorescence imaging provided better classification performance for some types of foreign matter. For transparent plastic materials, the hyperspectral fluorescence imaging achieved a classification rate of 96%, which was 50% higher compared with a hyperspectral reflectance imaging system that only achieved a classification rate of 44%.\textsuperscript{7} In addition, for seed coat inner and twine, the hyperspectral fluorescence imaging achieved classification rates of 92% and 100%, respectively, which were 22% and 33% fewer than the LDA.

![Figure 7](image_url) Loadings of the top three principal components. A total of 19 wavelengths (eight from each of the top three principal components) were selected by removing repeated wavelengths and used as features for classification.

<table>
<thead>
<tr>
<th>Foreign matter category</th>
<th>Lint</th>
<th>Paper</th>
<th>Pl. bag pack.</th>
<th>SCI</th>
<th>SCO</th>
<th>Seed</th>
<th>Twine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lint</td>
<td>96</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Paper</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pl. Bag</td>
<td>0</td>
<td>0</td>
<td>96</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Pl. Bale Pack</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>92</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>SCI</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>92</td>
<td>0</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>SCO</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>71</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>Seed</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>25</td>
<td>71</td>
<td>0</td>
</tr>
<tr>
<td>Twine</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

SCI: inner part of seed coat; SCO: outer part of seed coat.

Table 1. Linear discriminant analysis classification results for seven categories of foreign matter and lint
higher than what a fluorescence imaging system achieved. Therefore, the presented system showed a great improvement of classifying certain types of foreign matter compared with previous studies.

Although the classification results are promising, hyperspectral fluorescence imaging is only suitable for the foreign matter with abundant fluorophores. By nature, the hyperspectral imaging technique has a low light throughput, as only a small amount of light that passes through a thin slit is detected by the camera, and generally the intensity of fluorescence signals is low. As a result, the low fluorescence signal leads to a low signal-to-noise ratio (SNR) of the image, creating a challenge for data processing. In addition, in order to capture the low signal, the camera has to use a longer exposure time that is not suitable for online inspection systems. Another major limitation is that the current classification results were calculated by placing the foreign matter samples on top of lint. In fact, in commercially produced cotton samples, the foreign matter could be hidden or partially hidden underneath lint, and thus the classification accuracy could be reduced. These limitations of the proposed approach should be considered and addressed in future studies. In addition, other modalities also need to be included for a comprehensive classification of foreign matter.

Conclusion

This study explored the feasibility of using hyperspectral fluorescence imaging for solving the issue of foreign matter and lint differentiation and classification. A total of 19 wavelengths were selected as the optimal features for classification, including 430, 433, 437, 440, 464, 466, 469, 471, 474, 476, 479, 481, 520, 522, 525, 544, 547, 559, and 611 nm. They achieved an average classification rate of 90% for lint and seven types of foreign matter, including paper, plastic bags, plastic packaging, twine, seed, and seed coat inner and outer. The results demonstrated the great potential of using the hyperspectral fluorescence imaging system for classifying the foreign matter with strong fluorescence, such as paper and transparent plastics. Therefore, the system presented in this study could be used as a complementary tool for cotton quality assessment. Future studies will be focused on combining the hyperspectral fluorescence and reflectance modalities for classification of foreign matter, and applying the proposed system to detect and classify foreign matter hidden underneath cotton lint, as well as pepper trash. Besides, image segmentation algorithms need to be developed for automatically extracting non-lint samples and calculating their area.

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