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# Are yarn quality prediction tools useful in the breeding of high yielding and better fibre quality cotton (*Gossypium hirsutum* L.)?

LIU Shiming[1*], GORDON Stuart[2] and STILLER Warwick[1]

## Abstract

**Background** The approach of directly testing yarn quality to define fibre quality breeding objectives and progress the selection is attractive but difficult when considering the need for time and labour. The question remains whether yarn prediction tools from textile research can serve as an alternative. In this study, using a dataset from three seasons of field testing recombinant inbred line population, Cottonspec, a software developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for predicting ring spun yarn quality from fibre properties measured by High Volume Instrument (HVI), was used to select improved fibre quality and lint yield in the population. The population was derived from an advanced generation inter-crossing of four CSIRO conventional commercial varieties. The Cottonspec program was able to provide an integrated index of the fibre qualities affecting yarn properties. That was compared with selection based on HVI-measured fibre properties, and two composite fibre quality variables, namely, fibre quality index (FQI), and premium and discount (PD) points. The latter represents the net points of fibre length, strength, and micronaire based on the Premiums and Discounts Schedule used in the market while modified by the inclusion of elongation.

**Results** The population had large variations for lint yield, fibre properties, predicted yarn properties, and composite fibre quality values. Lint yield with all fibre quality traits was not correlated. When the selection was conducted first to keep those with improved fibre quality, and followed for high yields, a large proportion in the resultant populations was the same between selections based on Cottonspec predicted yarn quality and HVI-measured fibre properties. They both exceeded the selection based on FQI and PD points.

**Conclusions** The population contained elite segregants with improved yield and fibre properties, and Cottonspec predicted yarn quality is useful to effectively capture these elites. There is a need to further develop yarn quality prediction tools through collaborative efforts with textile mills, to draw better connectedness between fibre and yarn quality. This connection will support the entire cotton value chain research and evolution.

**Keywords** Yield, Fibre properties, Fibre quality index, Predictive yarn quality, Cotton marketing, Cotton breeding

*Correspondence:
Liu Shiming
Shiming.Liu@csiro.au
[1] CSIRO Agriculture and Food, Narrabri, NSW 2390, Australia
[2] CSIRO Agriculture and Food, Werribee, VIC 3030, Australia

## Introduction

Cotton is primarily produced for fibres supplied to textile mills where they are processed into yarn and various textile products. Over the value chain, fibre quality is of mutual interest to both cotton growers and processors (May and Taylor 1998; Bradow and Davidonis 2000; Kelly et al. 2015). Growers wish to produce a fibre quality that receives either no discount or a small premium. Poor quality fibre affects the value translation of field productivity into crop gross margin and reduces crop returns. To spinners, procuring cotton with an expected quality but low in price enables mills to produce the targeted quality in a more cost-controlled manner so that they can run a profitable and competitive business, as cotton remains the major cost component (Bourland et al. 2010; Constable et al. 2015; Yang and Gordon 2016).

New technologies have continuously increased the speed and efficiency of textile processes. Consumers also have an increased interest in cheap cotton brand products. Both factors have driven the ongoing changes in demands and specifications for high-quality cotton (Bradow and Davidonis 2000; Liu et al. 2010; Kelly et al. 2015). Breeding is a major contributor to improved fibre quality (Campbell et al. 2011; Clement et al. 2012; Kuraparthy and Bowman 2013; Constable et al. 2015), and continuing this effort becomes more important than ever while improving cotton productivity.

Cotton fibre quality is defined according to physical fibre properties, namely, fibre length (LEN, mm), strength (STR, $g \cdot tex^{-1}$) [0.980 is a conversion factor to express as $cN \cdot tex^{-1}$], micronaire (MIC), uniformity (UNI, %), short fibre index (SFI, %) and elongation (EL, %). Each of them has an influence on spun yarn and the finished products (Meredith et al. 1991; May and Taylor 1998; Kelly et al. 2015). High Volume Instrument (HVI) lines are widely used to measure these properties, from which breeders use for selection, merchants for determining sale prices, and spinners for deciding types of yarns to spin (Bourland et al. 2010; Kelly et al. 2015; Yang and Gordon 2016). Fibre properties are both heritable and influenced by the environment and the extent varies with traits and breeding populations (Coyle and Smith 1997; Meredith et al. 2012; Campbell and Myers 2015; Koebernick et al. 2019). Breeding for improved fibre quality is to ensure fibre properties meet the evolving demands of textile mills (Bourland et al. 2010).

Routine practice for fibre quality improvement is to assess and identify individual plants or lines with acceptable fibre properties. To warrant the translation of improved fibre properties into yarn quality, two approaches are commonly used in cotton breeding programs. One is to convert fibre property measurements into various composite indices based on their importance for spinning and use those numbers in the breeding selection. For example, the fibre quality index (FQI) or its modifications have commonly been used to assess the quality of cotton bales in textile mills (Lord 1961; Majumdar et al. 2005; Liu et al. 2011). More recently the Q-score based on normalised fibre LEN, STR, and MIC values has been developed and applied (Bourland et al. 2010). Using indices also simplifies selection and saves time (Bourland et al. 2010). Given the negative associations between fibre yield and quality, particularly via STR and LEN (Culp and Harrell 1973; Green and Culp 1990; Clement et al. 2012), the question remains on how index-based selections can affect yield improvement in cotton. The other is to directly conduct spinning tests, either using the industrial scale spinning setting (May and Taylor 1998; Long et al. 2010; Faulkner et al. 2012) or miniature lab-based spinning systems (Bradow and Davidonis 2000; Foulk et al. 2009; Liu et al. 2019). The approach is appreciated as it can verify the impact of improved fibre properties on resultant yarn quality. However, extensive use is difficult, as it is slow and expensive and is unable to assess the large number of individuals tested every season in breeding programs. However, there is an interest in resolving such challenges by developing predictive models from large textile mill datasets.

HVI measurements of cotton bales in textile mills are commonly used to assess the impact of fibre properties on yarn quality and to develop in-house predictive tools to facilitate decision-making mainly in cotton procurement and the making up of laydown for processing in the mills (Majumdar et al. 2005; Yang and Gordon 2016). Two types of predictive tools from fibre to yarn quality have been developed. One is based on the simple causational relation of fibre properties or their index numbers (e.g., FQI) with yarn properties (Ramey et al. 1977; Majumdar et al. 2005; Ureyen and Kadoglu 2006; Foulk et al. 2009; Liu et al. 2011). However, the effect of fibre properties on yarn properties can vary with the properties and spinning systems (Ramey et al. 1977; Ghosh et al. 2005; Ureyen and Kadoglu 2006). Yarn quality is also influenced by the intrinsic relation of different fibre properties as well as yarn structural factors (Faulkner et al. 2012; Yang and Gordon 2016). Therefore, these factors should be taken into account when developing predictive models (Hafez 1987; Ramesh et al. 2008; Yang and Gordon 2016).

Cottonspec is a software developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for textile mills to predict the yarn properties of medium to fine-count (30 tex (Ne 20) to 12 tex (Ne 50)) carded or combed ring-spun yarns based on HVI-measured fibre properties (Yang and Gordon 2016). The models were initially built and validated with large datasets from leading ring-spinning textile mills in China while taking account of the fibre properties, as well as the yarn specification (count and twist) and intrinsic yarn factors. The software has been used in textile mills in South-East Asian regions for around 10 years. However, how the models can be used to assist breeding for better fibre quality and higher-yielding cotton has not been investigated.

Nowadays, cotton bales are traded by the price schedule based on HVI-measured LEN, STR, MIC, colour, and trash content (Bradow and Davidonis 2000; Bourland et al. 2010). The schedule is updated yearly to reflect the changes for quality cotton in the market and premiums and discounts are applied to tell the potential of raw cotton processing into the end products. Using the market value of fibre quality was attempted in breeding selection but further research is required (Bourland et al. 2010). One of the limits is the current price schedule does not account for HVI-measured EL, but increased evidence demonstrates its importance for fibre resilience, consistency, and quality of resultant yarns (Benzina et al. 2007; Kelly et al. 2019; Mathangadeera et al. 2020). Thus, taking EL into account in the market value estimation of fibre quality is also important, even though its calibration standard for HVI remains to be adopted (Delhom et al. 2020).

Australia is one of the global leading cotton exporters not only producing the highest yield but supplying some of the best grades of raw cotton. Most of the Australian cotton is exported for ring spinning into medium to fine count yarns (30–12 tex) (Long et al. 2010; Yang and Gordon 2016). In this study, we examine how FQI, Cottonspec predicted yarn quality, and estimated premium and discount (PD) points are useful to assist our breeding efforts for higher-yielding and desired quality cotton when compared with our routine breeding selection based on the HVI-measured fibre quality. It is hypothesised that breeding effectiveness and progress can be further increased via streamlining and integrating the use of tools developed from the post-harvest value chain.

## Materials and methods

### Test population and field experiments

All test lines in this study are recombinant inbred lines (RILs) from a multi-parent advanced generation intercrossing among four released conventional cultivars, namely, Sicot 71 (Reid 2003), Sicot 75 (Stiller 2008), Sicot F-1 (Reid 2005a), and Siokra 24 (Reid 2005b). The parents were initially paired to make two crosses in 2011, and their $F_1$'s were crossed to derive a segregated population with over 1 000 $F_1$ seeds. The $F_1$ to $F_5$ generations were advanced according to the single seed descent method (SSD) to increase the homozygosity of single plants in the population from which RILs were derived. From the $F_7$ generation, 256 $F_6$-derived RILs were randomly selected and tested in single-row plot experiments with their four parents over the summer of 2016/2017, 2017/2018, and 2019/2020 in fields at Australian Cotton Research Institute (ACRI) near Narrabri, NSW, Australia (S30° 11', E149° 35'). The soil is a self-mulching Vertosol classified as a fine, thermic, montmorillonitic Typic Haplustert with high clay content (Soil Survey Staff 1996; Ward et al. 1999). The experiments were planted according to a row-column design with two replicates generated with DiGGer V. 1 software. Single row plots of 12 m length and 1 m row spacing represented units in the experiment.

The experiments were managed for fertilisers, irrigation, control of pests, and weeds according to the commercial farm practices (https://www.cottoninfo.com.au/publications/australian-cotton-production-manual), and chemically defoliated at the end of the season with thidazuron and ethephon when at least 60% of bolls were open. A single-row plot picker was used to harvest and record plot yield. About 250 g seed cotton sample was grabbed and kept at harvest of each plot and ginned with a 20-saw gin to separate lint and fuzzy seeds. The weight of the lint fraction was recorded and used to calculate lint percentage (LP) and the subsamples were kept for measuring fibre properties using a Uster 1000 High Volume Instrument following Guideline for Standardized Instrument Testing of Cotton (International Cotton Advisory Committee and International Textile Manufacturers Federation 2018).

### Lint yield and fibre properties

Plot yield recorded at harvest was multiplied with LP to convert lint yield into lint per hectare (LY, $kg \cdot ha^{-1}$) which was used in the data analysis. The HVI testing of lint samples recorded five fibre properties: fibre length (LEN), uniformity (UNI), short fibre index (SFI), fibre strength (STR), elongation (EL), and micronaire (MIC). In cotton quality assessment, SFI is defined as the proportion of fibre in a test fibre bundle by weight shorter than 12.7 mm in length, and in HVI test, it is estimated indirectly based on fibre length measurements (Kelly et al. 2015).

### Fibre quality index (FQI)

FQI is a multiplicative composite variable to transform measured fibre properties of LEN, STR, and fineness, i.e., MIC into a single value. Despite of different forms reported and used in textile mills (Lord 1961; Majumdar et al. 2005; Liu et al. 2011), in this study, a basic form according to the formula, $LEN \times UNI \times STR/MIC$, was used to calculate FQI numbers.

### Predicted yarn properties

In this study, two yarn properties, yarn evenness (YCV) and tenacity (YT), for English cotton fine count (Ne) 50 (11.8 tex) combed yarn were predicted by applying Cottonspec software and used to select for improved fibre properties. This count and type of yarn are typically used in the manufacture of high-quality light-weight knits and woven fabrics, e.g., for shirting. Our breeding effort is aimed at providing improved fibre properties that continuously meet the requirements of top-end yarn textile mills. Due to intellectual property protection, we are unable to disclose the algebra behind the predictions here. However, in the previous validation studies using textile mill datasets, yarn predicted values were highly correlated with measured YCV and YT in the mills where good quality control was practiced. The coefficients of determination ($R^2$) for the models ranged from 0.82 to 0.84 for YCV and 0.85 to 0.98 for YT (Yang and Gordon 2016).

### Premium and discount (PD) points

In Australia, cotton bales are classed and sold according to a yearly updated Premiums and Discounts Schedule Sheet (see an example via the link: A basic guide to cotton pricing and quality—Jan 2017.pdf (cottoninfo.com.au). In the Schedule, premium and discount points are tabulated in terms of the grades of HVI-measured fibre properties including LEN, STR, and MIC combined with fibre colour and trash content. When total points are determined for cotton bales, they are converted into US cents by the rate of 100 points to one and added onto the cotton price in the ICE Futures U.S. Cottons No. 2 Futures as the bale price for sale. The system is similar to the loan scheme used in cotton sales under USA Commodity Credit Corporation (CCC) Loan Premiums and Discounts (Bourland et al. 2010).

In this study, harvest cotton samples were ginned using experimental gin after pre-cleaning and the fibre properties were tested with HVI. In the process, however, trash and colour were not assessed or recorded, therefore, we can only assume these properties were in acceptable ranges with zero premium and discount. On the other hand, there is an increased recognition of the importance of EL in both yarn spinning and fabric manufacturing, despite no calibration HVI standard available hampering its inclusion and assessment in cotton classing and trading. In this study, all samples were measured by the same single HVI in our laboratory so that different experiments could be compared without calibration (Benzina et al. 2007). In order to reflect its importance in breeding better fibre quality cotton, we developed a premium and discount points range for EL, using the range of fibre elongation values observed in *G. hirsutum* germplasm and also the minimal elongation (4%) required for fibre spinning and weaving (Benzina et al. 2007; Kelly et al. 2019; Mathangadeera et al. 2020) (Additional file 1, Table S1). According to the HVI measured fibre properties, we derived the correspondent premium and discount points for each trait, and the sum represents premium and discount (PD) points for data analysis and breeding selection of fibre property package.

### Statistical analysis

The dataset from three season experiments were pooled together and analysed as a multi-environmental trial with a mixed model (Smith et al. 2005). Test lines, season, and their interaction were fitted as fixed and spatial variations, i.e., global and extra effects associated with the block structure of the experiment, were taken into account following our previous study (Liu et al. 2015). The empirical best linear unbiased estimates (E-BLUEs) obtained for RILs and four parents were used in retrospect selection as described below.

### Comparison of selection effectiveness

Improved overall fibre quality is achieved by the selection of HVI-measured fibre properties, FQI number, Cottonspec predicted yarn properties and PD points. For each selection practice, truncating points for the traits were determined when considering the means of parents and population as well as the breeding objective of fibre quality and selection was applied to keep approximately 33% of the entire population. The resultant populations were compared for their means and variation in lint yield, fibre properties, and the proportion of RILs commonly retained, and whether yield variations were maintained as such from which further selection resulted in the improved combinations for both yield and fibre quality. For all the comparisons, the resultant population from selection based on the HVI-measured fibre properties were used as references, as that is a common practice in current cotton breeding programs.

All analyses were carried out using ASreml-R (Butler et al. 2018) and R (R Core Team 2022).

## Results

### Phenotypic variation for line yield, fibre properties, predicted yarn properties, and the composite quality traits

Four parents used for crossing showed larger difference in LY, SFI, FQI, and PD points but smaller for UNI, STR, and EL with the remaining properties being within these differences (Table 1). Sicot 71 was the highest yielder but had short and coarse fibre resulting in the lowest predicted yarn quality and minus PD points (Additional file1, Table S2). In contrast, Sicot 75 and Siokra 24, despite not being the best yielders, possessed good fibre properties, especially LEN and STR, which translated to the best-predicted yarn quality as well as positive PD points. Sicot F-1 was the lowest yielder and had shorter fibre, but high STR made it a base grade fibre quality with small PD points and intermediate predicted yarn quality.

The phenotypic variations for all traits in the population are shown in Table 1. When compared with the parent means, the population exhibited higher for LY, LP, and EL, but lower for SFI, FQI, and PD points and

**Table 1** Descriptive statistics of yield, lint percentage, fibre properties, fibre quality index, premium and discount points, and predicted yarn properties for the parents and population

| Trait | Parent | | | Population | | |
|---|---|---|---|---|---|---|
| | Mean | Range | CV /% | Mean | Range | CV /% |
| LY /(kg·ha$^{-1}$) | 2 091 | 1 777–2 372 | 14.21 | 2 287 | 1 376–2 747 | 7.62 |
| LP /% | 40.1 | 37.9–42.4 | 5.67 | 42.4 | 32.7–47.0 | 4.26 |
| LEN /mm | 31.4 | 30.0–33.1 | 4.44 | 31.4 | 26.9–34.2 | 3.77 |
| UNI /% | 84.8 | 84.1–85.5 | 0.78 | 84.9 | 83.1–86.5 | 0.83 |
| SFI /% | 6.3 | 5.3–6.8 | 10.98 | 6.0 | 4.7–7.4 | 8.01 |
| STR /(g·tex$^{-1}$) | 31.5 | 31.1–31.9 | 1.23 | 31.2 | 28.2–34.4 | 4.03 |
| EL /% | 5.5 | 5.3–5.6 | 2.71 | 5.8 | 4.5–7.3 | 9.16 |
| MIC | 4.5 | 4.2–4.6 | 3.89 | 4.6 | 3.2–5.5 | 6.4 |
| FQI | 191.0 | 171.0–208.2 | 8.7 | 182.5 | 130.7–247.4 | 10.0 |
| YCV /% | 10.1 | 9.7–10.4 | 3.28 | 10.1 | 9.0–11.1 | 3.38 |
| YT /(cN·tex$^{-1}$) | 20.5 | 19.7–21.1 | 3.15 | 20.1 | 17.8–22.5 | 4.54 |
| PD points | 13.1 | -45.6–52.9 | 340.1 | -77.1 | -1 578.1–97.9 | -255.8 |

*CV* Coefficient of Variance, *LY* lint yield, *LP* lint percentage, *LEN* fibre length, *UNI* fibre uniformity, *SFI* short fibre index, *STR* fibre strength, *EL* fibre elongation, *MIC* fibre micronaire, *FQI* fibre quality index, *YCV* yarn evenness, *YT* yarn tenacity, *PD points* Premium and Discount points

comparable for the other traits. Variations followed normal distributions with larger variability in LY, SFI, EL, MIC, FQI, and PD points (absolute CV > 6%) and the smallest in UNI (CV < 1%). Distributions skewed to small values for LY, LP, LEN, MIC, and PD points and with a large number of individuals around the means for LY, LP, MIC, and PD points (Kurtosis > 4.5, $P < 0.001$) (Additional file 1, Table S3). However, transgressive segregants, measured as either higher or lower than the best or worst parent, existed for all the traits. There was a proportion of 20% to 63% of individuals better than the best parent for LY, LP, UNI, STR, EL, and PD points, 12% more for the predicted YCV, and YT and 20% with the desirable range of MIC value (3.8 to 4.9). Therefore, the intercrossing of diverse commercial varieties resulted in large segregation and recombination in both lint yield and fibre quality traits.

### Interrelation of yield, lint percentage, fibre quality properties, and composite quality traits

The direction and magnitude of trait interrelations are given in Table 2. LY exhibited a moderately positive relation with LP, but only occasionally with fibre properties and their converted index number or predicted quality traits. Even when the relations existed, they were generally weak and/or may vary in direction with experimentation seasons. LP was positively correlated with EL, MIC, and YCV but negatively with LEN, FQI, and YT, however, the relation was weak ($r$ = -0.312 to 0.309). LEN was positively correlated with UNI, FQI, STR, YT, and PD points, but negatively with SFI, EL, MIC, and YCV, in most cases being moderate ($0.33 < |r| < 0.66$) to strong ($|r| \geq 0.66$) but weak ($|r| \leq 0.33$) with STR. UNI showed positively weak to moderate relations with STR, FQI, YT, and PD points but negative ones with SFI and YCV with magnitude ranged from strong to weak. SFI had a positive correlation with YCV but negative with STR, FQI, YT, and PD points, either strong or weak. STR was moderately positively correlated with FQI and YT but weak negatively with EL. EL was positively correlated with MIC and YCV but negatively with FQI, YT, and PD points, ranging from weak to moderate. MIC, FQI, YCV, and YT were correlated one another over the experiments. The relations were positive and moderate in magnitude, when FQI and YT paired with PD points, respectively, but exhibited strong when MIC paired with YCV and FQI with YT. The rest of the trait pairs had negative relations, ranging from moderate to strong. Strong and consistent relations among MIC, FQI, and YCV but often in opposite directions support the great influence of fibre fineness on spinning performance and yarn quality.

### Comparison of selections for better fibre quality and high yield

Keeping the best 33% of the population when selecting desired fibre quality combinations resulted in the retention of 82 to 86 individual lines, regardless of which selection was used (Table 3). The selected population based on HVI-measured fibre properties was less consistent with those by others, as only 52.3% to 61.6% of individuals in the resultant populations were identical with the highest consistency being with the result of selection based on Cottonspec predicted yarn properties. The consistency increased to 67.1% or more in the resultant populations

**Table 2** Correlation coefficient and significance of yield, lint percentage, fibre quality properties, predicted yarn properties and other composite fibre quality values from mean estimates of analysis of individual and combined season experiments

| Trait | Season | LP | LEN | UNI | SFI | STR | EL | MIC | FQI | YCV | YT | PD points |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LY | 2016/2017 | 0.484*** | -0.211*** | -0.204*** | 0.257*** | ns | ns | ns | -0.195** | 0.201*** | -0.191** | ns |
| | 2017/2018 | 0.542*** | ns | ns | -0.299*** | ns | ns | ns | ns | -0.130* | ns | ns |
| | 2018/2019 | 0.665*** | ns | ns | ns | ns | ns | 0.133* | ns | 0.126* | ns | 0.120* |
| | Combined | 0.689*** | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| LP | 2016/2017 | | -0.309*** | -0.182** | 0.320*** | ns | 0.159** | 0.194** | -0.294*** | 0.312*** | -0.255*** | ns |
| | 2017/2018 | | -0.207*** | ns | -0.481*** | ns | 0.185** | 0.127* | -0.198*** | ns | ns | ns |
| | 2018/2019 | | -0.138* | ns | ns | ns | ns | 0.279*** | -0.273*** | 0.251*** | -0.235*** | ns |
| | Combined | | -0.228*** | ns | ns | ns | 0.164** | 0.225*** | -0.294*** | 0.191** | -0.191** | ns |
| LEN | 2016/2017 | | | 0.526*** | -0.741*** | ns | -0.491*** | -0.529*** | 0.761*** | -0.794*** | 0.607*** | 0.453*** |
| | 2017/2018 | | | 0.553*** | ns | 0.276*** | -0.353*** | -0.435*** | 0.743*** | -0.412*** | 0.446*** | 0.590*** |
| | 2018/2019 | | | 0.299*** | -0.401*** | 0.286*** | -0.422*** | -0.494*** | 0.773*** | -0.648*** | 0.614*** | 0.566*** |
| | Combined | | | 0.465*** | -0.416*** | 0.161** | -0.529*** | -0.514*** | 0.761*** | -0.713*** | 0.614*** | 0.453*** |
| UNI | 2016/2017 | | | | -0.707*** | ns | ns | ns | 0.402*** | -0.451*** | 0.353*** | 0.209*** |
| | 2017/2018 | | | | ns | 0.390*** | ns | -0.159** | 0.509*** | -0.153* | 0.311*** | 0.378*** |
| | 2018/2019 | | | | -0.851*** | 0.354*** | ns | ns | 0.355*** | -0.645*** | 0.574*** | 0.207*** |
| | Combined | | | | -0.625*** | 0.296*** | ns | ns | 0.402*** | -0.350*** | 0.369*** | 0.209*** |
| SFI | 2016/2017 | | | | | -0.119* | 0.245*** | 0.268*** | -0.569*** | 0.711*** | -0.549*** | -0.182** |
| | 2017/2018 | | | | | ns | ns | ns | ns | 0.399*** | -0.193** | ns |
| | 2018/2019 | | | | | -0.440*** | ns | ns | -0.438*** | 0.779*** | -0.704*** | -0.176** |
| | Combined | | | | | -0.277*** | ns | ns | -0.569*** | 0.481*** | -0.425*** | -0.182** |
| STR | 2016/2017 | | | | | | -0.348*** | 0.165** | 0.363*** | ns | 0.562*** | ns |
| | 2017/2018 | | | | | | -0.280*** | ns | 0.554*** | ns | 0.575*** | 0.214*** |
| | 2018/2019 | | | | | | -0.187** | ns | 0.494*** | -0.322*** | 0.659*** | 0.194** |
| | Combined | | | | | | -0.299*** | 0.126* | 0.363*** | ns | 0.575*** | ns |
| EL | 2016/2017 | | | | | | | 0.241*** | -0.501*** | 0.318*** | -0.467*** | ns |
| | 2017/2018 | | | | | | | 0.279*** | -0.405*** | 0.246*** | -0.352*** | -0.242*** |
| | 2018/2019 | | | | | | | 0.294*** | -0.375*** | 0.128* | -0.209*** | -0.264*** |
| | Combined | | | | | | | 0.380*** | -0.501*** | 0.387*** | -0.486*** | -0.108*** |
| MIC | 2016/2017 | | | | | | | | -0.779*** | 0.859*** | -0.668*** | -0.557*** |
| | 2017/2018 | | | | | | | | -0.790*** | 0.876*** | -0.793*** | -0.684*** |
| | 2018/2019 | | | | | | | | -0.791*** | 0.679*** | -0.609*** | -0.492*** |
| | Combined | | | | | | | | -0.779*** | 0.856*** | -0.687*** | -0.557*** |
| FQI | 2016/2017 | | | | | | | | | -0.861*** | 0.952*** | 0.441*** |
| | 2017/2018 | | | | | | | | | -0.710*** | 0.883*** | 0.687*** |
| | 2018/2019 | | | | | | | | | -0.835*** | 0.908*** | 0.536*** |
| | Combined | | | | | | | | | -0.861*** | 0.952*** | 0.441*** |
| YCV | 2016/2017 | | | | | | | | | | -0.758*** | -0.510*** |
| | 2017/2018 | | | | | | | | | | -0.841*** | -0.661*** |
| | 2018/2019 | | | | | | | | | | -0.904*** | -0.450*** |
| | Combined | | | | | | | | | | -0.819*** | -0.510*** |
| YT | 2016/2017 | | | | | | | | | | | 0.395*** |
| | 2017/2018 | | | | | | | | | | | 0.662*** |
| | 2018/2019 | | | | | | | | | | | 0.473*** |
| | Combined | | | | | | | | | | | 0.395*** |

*LY* lint yield, *LP* lint percentage, *LEN* fibre length, *UNI* fibre uniformity, *SFI* short fibre index, *STR* fibre strength, *EL* fibre elongation, *MIC* fibre micronaire, *FQI* fibre quality index, *YCV* yarn evenness, *YT* yarn tenacity, *PD points* Premium and Discount points, *ns* non-significant

*, **, *** represent significance at $P < 0.05$, 0.01, and 0.001, respectively

**Table 3** The number and proportion of common lines retained by different selection methods for desirable fibre quality under selection intention of keeping 33 percentage of the population

| Selection method | Total number of retained lines | Number of lines commonly identified | | |
|---|---|---|---|---|
| | | Fibre quality index | Yarn properties | Premium and discount points |
| HVI fibre properties | 86 | 50 (58.1%) | 53 (61.6%) | 45 (52.3%) |
| Fibre quality index | 85 | | 66 (77.6%) | 58 (68.2%) |
| Yarn properties | 82 | | | 55 (67.1%) |
| Premium and discount points | 86 | | | - |

selected by the other methods and a highest of 77.6% was observed between selections based on FQI numbers and Cottonspec predicted yarn quality, suggesting the underlying resemblance of an integrated index or predicted values when used for selection for better fibre quality.

The mean and variation of fibre properties of the selected populations were given in Table 4. Overall, selection shifted the mean of fibre properties to the target direction and range. When comparing the population selected based on HVI-measured fibre properties, the populations retained based on the other methods maintained the comparable means but extended the variability for LEN, STR and MIC, suggesting that the lines being outside the truncation ranges based on their HVI-measured fibre properties were kept when the other methods were used for selection. For UNI and EL, selection with the other methods reduced the variation in the resultant populations, particularly for EL, resulting in more lines with low EL retained, which is undesirable.

The number of lines in the selected population belonging to relative lint yield quartiles of the entire population is given in Table 5. Interestingly, regardless of the traits used in selection for better fibre quality, there were more than 54% of retained lines with yields ranking in the top two quartiles (46 to 49 lines). Furthermore, selection based on Cottonspec predicted yarn properties resulted in retaining the highest proportion of high-yielding lines commonly kept based on HVI-measured fibre properties (62%), followed by FQI numbers (58%) and the least for PD points (50%).

Relative yield distributions of the unselected and selected populations are given in Fig. 1. The mean of the resultant population based on selection using FQI numbers and PD points very much unchanged, when compared with those kept by selection based on HVI-measured fibre properties and Cottonspec predicted yarn properties. Consequently, there were fewer lines with yield potential better than the mean of the population being captured after selection with FQI and PD points. The key reason behind this was selection resulted in reducing or discarding the lines in the top-yielding bins, which was more obvious in the resultant population based on FQI and best yielders (relative lint yields ≥ 109%) were dismissed. In contrast, the selected population based on Cottonspec predicted yarn properties captured a greater number of test lines in the highest-yielding bin, for examples, increased number of test lines kept for relative lint yield of 105–107% and 115%. This is consistent with the results aforementioned and suggests the merits of predicted yarn quality selection

**Table 4** Comparison of six fibre properties between the unselected and selected populations from four different methods for best fibre quality combinations

| Trait | Mean and range of population | Mean and range of selected population by different methods | | | |
|---|---|---|---|---|---|
| | | HVI fibre properties | Fibre quality index | Yarn properties | Premium and discount points |
| LEN /mm | 31.4 (26.9–34.2) | 32.0 (31.1–34.2) | 32.2 (30.5–34.2) | 32.2 (30.0–34.2) | 32.2 (30.8–34.2) |
| UNI /% | 84.9 (83.1–86.5) | 85.2 (83.3–86.5) | 85.1 (83.7–86.5) | 85.2 (83.7–86.5) | 85.2 (83.7–86.5) |
| SFI /% | 6.0 (4.7–7.4) | 5.8 (4.8–6.5) | 5.9 (4.7–7.2) | 5.7 (4.7–7.0) | 5.9 (4.7–7.2) |
| STR /($g \cdot tex^{-1}$) | 31.2 (28.2–34.4) | 31.7 (30.5–33.9) | 31.8 (28.9–34.4) | 31.6 (29.1–34.2) | 31.5 (29.0–34.2) |
| EL /% | 5.8 (4.5–7.3) | 5.7 (5.0–7.1) | 5.5 (4.7–6.5) | 5.6 (4.8–6.5) | 5.6 (4.8–6.7) |
| MIC | 4.6 (3.2–5.5) | 4.5 (4.0–4.9) | 4.4 (3.9–5.0) | 4.4 (3.9–4.7) | 4.4 (3.9–4.9) |

The values in brackets represent the ranges of traits

**Table 5** The number of lines in the selected populations for better fibre quality belonging to different quartiles of relative lint yield of the unselected population calculated against a parent, Sicot 71 under different selection methods and the proportion of their commonality with those kept by the selection based on HVI-measured fibre properties

| Selection methods for fibre quality | Relative lint yield ranges of different quartiles | | | |
|---|---|---|---|---|
| | ≤92 % | 92%–97 % | 97%–100 % | >100 % |
| HVI fibre properties | | | | |
| Number of lines retained | 11 | 26 | 21 | 28 |
| Fibre quality index | | | | |
| Number of lines retained | 20 | 19 | 20 | 26 |
| Common to those by fibre properties | 7 (35.0) | 13 (68.4) | 15 (75.0) | 15 (57.7) |
| Different to those by fibre properties | 13 (65.0) | 6 (31.6) | 5 (25.0) | 11 (42.3) |
| Predicted yarn properties | | | | |
| Number of lines retained | 15 | 18 | 20 | 29 |
| Common to those by fibre properties | 7 (46.7) | 14 (77.8) | 14 (70.0) | 18 (62.1) |
| Different to those by fibre properties | 8 (53.3) | 4 (22.2) | 6 (30.0) | 11 (37.9) |
| Premium and discount points | | | | |
| Number of lines retained | 21 | 19 | 22 | 24 |
| Common to those by fibre properties | 6 (28.6) | 10 (52.6) | 17 (77.3) | 12 (50.0) |
| Different to those by fibre properties | 15 (71.4) | 9 (47.4) | 5 (22.7) | 12 (50.0) |

The values in brackets represent the proportion /%

for breeding high yielding and better-quality cotton, although the routine selection practice based on HVI-measured fibre properties performed comparably well.

## Discussion

A grower's cotton will be eventually transformed into the end-use products, yarn and fabrics that matter to our daily life. There is a long and strong advocacy to link yarn quality with its farm-gate fibre quality to assist and direct the on-farm research to enhance crop performance, resilience, and profitability (Bradow and Davidonis 2000; Bourland et al. 2010; Liu et al. 2019). Using direct spinning tests is challenging, particularly in terms of the considerable input of time and labour to prepare and process sufficient lint before conducting the spinning tests, regardless of what scale settings, e.g., industrial, pilot or miniature spinning systems (Meredith et al. 1991; Foulk et al. 2009; Long et al. 2010; Faulkner et al. 2012). For breeding programs, where selections are made on hundreds or thousands of single plants and test lines, it is prohibitive, given the short time available before breeders can use the information to make decisions on selection.

This study tested the alternatives using the tools developed in textile mills to quantify the end-use value of fibre bales for breeding selection. In contrast to previous research aiming to develop in-house prediction models using limited field experiments and spinning tests conducted for breeding selections (Meredith et al. 1991; Benzina et al. 2007; Faulkner et al. 2012; Liu et al. 2019), we assessed the value of three widely used tools existing in the post-harvest value chain research for cotton breeding selection. These tools are FQI numbers (Majumdar et al. 2005; Liu et al. 2011), PD points from Premiums and Discounts Schedule used in today's cotton classing and trading, and predicted yarn properties from Cottonspec, which is a CSIRO-developed software based on a large ring spinning mill dataset (Yang and Gordon 2016). When they were used for sequential selection for simultaneously improving fibre quality and yield in the test population (Table 1), selection based on Cottonspec predicted yarn properties for fibre quality resulted in a population with better yield when compared with those retained by the other tools examined (Table 5 and Fig. 1). When compared with the resultant population by the routine selection based on HVI fibre properties, a large proportion of individuals in the retained populations was identical, and more interestingly, a greater number of the highest yielding RILs were kept under selection based on Cottonspec predicted yarn properties (Fig. 1). Thus, Cottonspec is a good and rapid tool for selecting improved fibre quality while maintaining good yield variation and potential in the resultant population.

Australian cotton is mainly supplied to ring spinning mills that produce high-end quality yarns (Long et al. 2010; Yang and Gordon 2016), under which HVI-measured LEN, UNI, STR, and MIC, strictly speaking, fibre fineness, are known to play a great influential role on ring-spun yarn quality (Ramey et al. 1977; Meredith et al. 1991; May and Taylor 1998; Bourland et al. 2010;

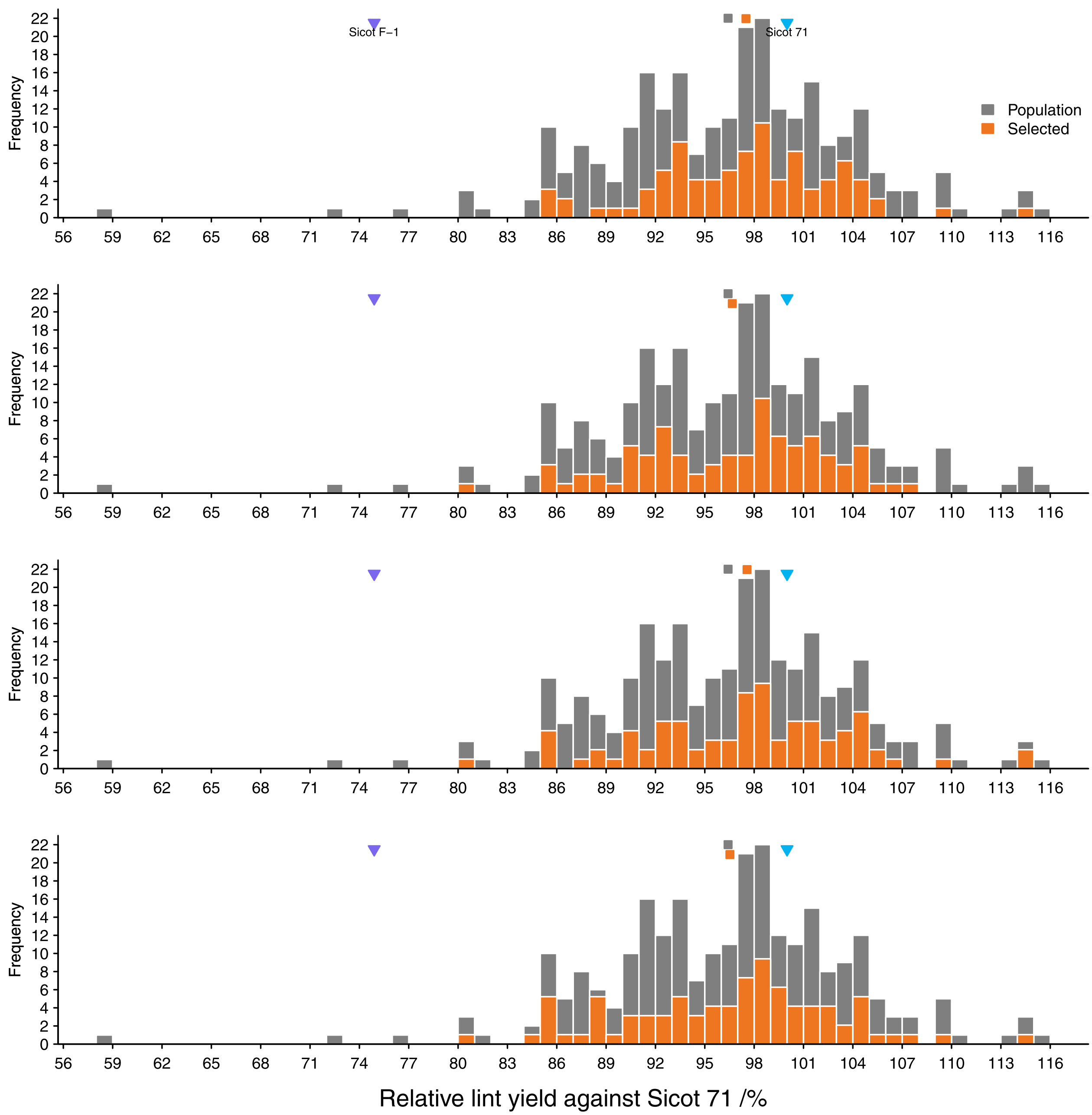


**Fig. 1** Distribution of relative lint yield against the highest yield parent, Sicot 71, in the populations prior- and post-selection for fibre quality based on HVI-measured fibre properties (top), fibre quality index (FQI, 2nd), Cottonspec predicted yarn properties (3rd) and premium and discount (PD) points (bottom). Down triangles represent relative yields of the lowest and highest yielding parents; Squares represent the means of the unselected and selected populations

Kelly et al. 2015). Better agreed outcomes in selections between HVI-measured fibre quality and Cottonspec predicted yarn properties suggest that the latter can fairly describe and reflect the core breeding objective for fibre quality in the CSIRO cotton breeding program. However, that is not the case for selection based on FQI and PD points, as their resultant populations after selection contained a reduced number of individuals common to those selected based on HVI-measured fibre properties, and they kept more lower yields while excluding individuals with higher yields (Tables 3 and 5; Fig. 1). Therefore, both FQI and PD points in the current forms are not useful in breeding selection for the improved combinations of yield and fibre quality.

The shortfall in the ability for FQI and PD points to be used in selection can be explained as:

1) The relative importance of HVI fibre properties. In ring-spun yarns, fibre strength is the number one influential factor on yarn tenacity, but fibre length and fineness also played an important role either independently or by their interactions with other properties in the yarn structure (Ramey et al. 1977; Meredith et al. 1991). Unfortunately, this complex is not fully captured in the FQI formula. Majumdar et al. (2005) demonstrated the use of a multiplicative analytic hierarchy process to find and assign the different power for involved fibre properties in the FQI formula. The power could reflect their relative importance in spinning processes. When modified FQI was used in the calculation, the resultant numbers showed a much stronger association with ring-spun yarn tenacity. PD points in this study represent the net sum premium and discount of four fibre properties, i.e., LEN, STR, EL, and MIC. The points of each trait can reflect their relative importance. However, PD points were not distributed normally where more than 41% population concentrated in the zero to positive ranges with small variability (Table 1; Additional file 2, Fig. S1), which is similar to the distribution of fibre premium and discount values calculated from USDA Commodity Credit Corporation Loan Value (Bourland et al. 2010). This characteristic can limit the discrimination of breeding lines for selection and may also unintentionally exclude high yielding RILs.
2) Discount the impact of important traits and conditions on estimation. SFI is one of the major HVI-measured fibre properties associated with YCV. Short fibres are increased during ginning, cleaning, and prior-spinning preparations, with the accumulated broken long fibres over mechanical processes (Yang and Gordon 2016). In both the FQI number and PD point estimations used in this study, SFI is not included. However, there are studies that different FQI formulas counting for the SFI effect could improve their predictiveness for both yarn tenancy and evenness (Majumdar et al. 2005; Liu et al. 2011, 2019). In Cottonspec, the multiple linear regression model for yarn evenness predictions counts on SFI contribution, and via yarn evenness, it influences yarn tenacity based on yarn weak link theory (Yang and Gordon 2016). The current PD points version does not consider both UNI and SFI, as they are not considered or valued in current cotton classing and trading systems.
3) Both FQI and PD points are essentially transformed composite variables based on solely HVI measured fibre properties or price points, thus they completely ignore the effect of spinning setting, for example, twist, yarn count, and yarn structure on yarn properties (Hafez 1987; Ureyen and Kadoglu 2006; Yang and Gordon 2016). It is not surprising that they were not as competitive and effective as Cottonspec predicted yarn properties in breeding selection.

Moderate relation between lint yield and LP suggests higher LP is one of the key contributors to higher yielding in the population. This agrees with a trend in cotton breeding that genetic progress made for cotton yield continuously relies on selecting for high lint fraction of harvest yield (Campbell et al. 2011; Conaty and Constable 2020). In the population, the proportion of RILs with LP higher than the highest parent, Sicot 75, was dominant (30%), demonstrating how single parents can drive and skew trait segregation and distribution. Sicot 75 is known for its small seeds with weak seed and seedling vigour. Similar phenomena were also observed in the USA breeding programs (Snider et al. 2014; Dowd et al. 2018). Therefore, for those selected lines with improved yielding and better fibre quality, further work requires to see whether they possess seeds meeting the standards of planting seed quality for growing commercial crops. Our future paper will focus on how to achieve the right balances between seed size, lint fraction, and fibre quality at seed levels based on a good understanding of seed yield trait interrelations while breeding for high lint yielding and better-quality cotton.

That absence of a strong inverse relation between lint yield, HVI-measured fibre properties and other composite traits in the population was interesting. The finding explains why the resultant populations after truncation selection for improved fibre properties still contained sufficient variation for lint yield from which high lint yields can be captured and why a large proportion of the selected populations remain common despite of different trait forms, combinations or nature used in the initial screening for better fibre quality. However, this disagrees with previous studies in which undesired relations were common, for example, yield with LEN and STR (Culp and Harrell 1973; Clement et al. 2012; Koebernick et al. 2019). Australian cotton germplasm is known for its superior fibre quality, especially LEN and STR. The exploitation and utilisation of Australian germplasm in USA cotton breeding programs in recent decades were reported to one of the key elements behind the improved LEN and STR of the released cultivars (Kuraparthy and Bowman 2013). Clement et al. (2012) further demonstrated the negative relations between yield and STR and LEN were weaker in high-quality advanced breeding materials bred and tested in Australia than USA. Taken together, we expect future simultaneous breakthroughs for high productivity and better fibre quality will come more often from Australian breeding efforts and subsequently, that will continuously help global cotton genetic improvement. Furthermore, LEN and MIC are essentially two components of LP, as one represents fibre volume, and the other is fibre weight. The negative and unfavourable relations of these traits suggest LEN and MIC need to be particularly watched in breeding for high yield with improved fibre quality. Using alternative traits, such as fibre density (Clement et al. 2014), may avoid the selection pitfall of short and coarse fibre quality in combination with high yielding. HVI-reported MIC is known to be the outcome of both fibre fineness and maturity (Kelly et al. 2015), breeding programs are encouraged to use the instruments, for examples, AFIS and FMT, to measure and screen fibre fineness and maturity.

The nature and extent of interrelations between HVI-measured fibre properties suggest selection for the combination of long, higher length uniformity, strong, and fine fibres was feasible in the population, but there were challenges for combining long, strong, and fine fibres with increased fibre extensibility (EL) (Table 2). It is clear when EL is ignored (FQI and Cottonspec predicted yarn properties) or given little emphasis (PD points) (Table 4), selections resulted in discarding the RILs with best EL while retaining the RIL with low EL. In contrast, that was ultimately avoided when using the routine selection practice, as individual HVI-measured fibre property was checked and scrutinised. Better EL has been emphasised recently for its important roles in textile processes to reduce stoppages and increase processing efficiency as well as improve yarn evenness and tenacity (Ureyen and Kadoglu 2006; Faulkner et al. 2012; Kelly et al. 2019; Mathangadeera et al. 2020). Therefore, to avoid the reductions for EL when using the other tools in selection for fibre properties, their new versions need to appropriately account for the EL effect.

In this study, EL was one of the uncalibrated HVI measures from our laboratory but was done by a single HVI. Despite subjecting to the influence of experiment seasons, EL was less affected by genotype × season interaction (broad sense heritability ($H^2$) = 0.77), which is very similar to LEN ($H^2$ = 0.88) and STR ($H^2$ = 0.82). Thus, EL can be measured as reliable as other important fibre quality traits, in agreement with previous studies for fibre properties (Meredith et al. 1991, 2012). More interestingly, despite no large difference existed among the four parents, the variation for EL in the population was substantial where there was a proportion of 63% of the population with EL exceeding the best parental value (5.6). Therefore, our evidence supports Delhom et al. (2020)'s conclusions that the uncalibrated EL from a single HVI can be used for the selection of improved fibre extensibility in the population. The negative weak relation between fibre strength and elongation in this study is consistent with many previous studies (May and Taylor 1998; Benzina et al. 2007; Faulkner et al. 2012).

Interrelations between HVI-measured fibre properties with FQI, Cottonspec predicted YCV and YT and PD points suggest that low EL and high MIC and SFI results in generally low FQI numbers, and shorter, poor uniform and coarse fibres with high SFI would lead to more uneven and weak predicted yarn properties. Longer and more uniform fibres would reward higher PD points, i.e., premiums, while lower EL and higher MIC reduced PD points, i.e., discounts. All these evidences describe the relative importance of appraising fibre quality using estimated composite or predicted values. A very strong interrelation between FQI and predicted YCV and YT explains why they can pick up a large proportion of the same individuals in the populations when used for fibre quality selections (Table 3).

Cottonspec is a yarn quality prediction software developed using large datasets from leading ring-spinning mills in China. It is particularly relevant to ring-spun medium to fine-count yarns that are in high demand in the market. Cautions should be taken when used in breeding cotton aiming at the other spinning systems. The current software version does not count for the effect of fibre EL on yarn properties; further research and upgrade are needed. Following the same token, to ensure the timely reflection of the ongoing evolutions in market demands for quality cotton fibres, future research should be continued to develop more robust predicted models through exploiting big datasets from spinning mills using more advanced data analytic tools, for example, artificial intelligence and machine learning. Overall, this study does exemplify how the tools developed from the post-harvest value chain can be potentially used in cotton improvement and how they can support and bridge the connectedness and impacts of the field to post-harvest research and development efforts in the cotton value chain.

## Conclusions

In this study, three tools existed in cotton post-harvest value chain were examined for their effectiveness on selecting desired fibre properties and subsequently impact on capturing higher yielders in a four-way cross derived RIL population. Evidently, intercrossing multiple and diverse parents can lead to the emerge of recombinants with improved yield and fibre quality in the population. Selection first for desired fibre properties would truncate the variation of yield of the selected population, however, the extent varied with the tools of selection. Cottonspec predicted yarn quality exceeded both FQI and PD points in terms of retaining high yielders, and also showed good competitive to the routine selection practice based on

HVI-measured fibre quality. Therefore, Cottonspec predicted yarn quality can be used in preceding selection as a replacement of, or in a complementary manner with the routine selection practice used HVI-measured fibre properties. The significance of this change in the practice should help breeders much quicker glance at how the improvement made at fibre levels impact the quality of end-use products. They can use that information to define fibre quality breeding objectives and in a broader sense, fibre quality goals for the entire cotton value chain from field researchers, growers, traders, and processors so that they can work and invest together in the directions from which the resultant development in technologies can advance global cotton production and utilisation.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42397-023-00155-w.

**Additional file 1: Table S1.** A proposed Premium and Discount Points for fibre elongation in this study to estimate fibre quality market value. **Table S2.** Parental means of yield, HVI-measured fibre properties, the composite fibre quality traits and Cottonspec predicted yarn properties. **Table S3.** Skewness and kurtosis for lint yield, lint percentage, HVI-measured fibre properties, other composite fibre quality traits and Cottonspec predicted yarn properties.

**Additional file 2: Fig. S1.** Distribution of Premium and Discount points in the recombinant inbred line population. Downward triangles repesent means of the population (red) and parents (other colours).

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**Authors' contributions**

Liu S and Gordon S conceived and designed the study. Liu S and Gordon S collated and analysed data and prepared the first draft. Liu S, Gordon S, and Stiller W commented and revised the manuscript. All authors read and approved the final manuscript.

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**Availability of data and materials**

The data that supports the findings of this study can be provided upon reasonable request.

## Declarations

**Ethics approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

**Competing interests**

Authors declare no conflict of interests.

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**References**

Benzina H, Hequet E, Abidi N, et al. Using fiber elongation to improve genetic screening in cotton breeding programs. Textile Res J. 2007;77:770–8. https://doi.org/10.1177/0040517507080689.

Bourland FM, Hogan R, Jones DC, Barnes E. Development and utility of Q-score for characterizing cotton fiber quality. J Cotton Sci. 2010;14:53–63.

Bradow JM, Davidonis GH. Quantitation of fibre quality and the cotton production-processing interface: a physiologist's perspective. J Cotton Sci. 2000;4:34–43.

Butler DG, Cullis BR, Gilmour AR, et al. ASReml-R reference manual version 4. Hemel Hempstead. UK: VSN International Ltd; 2018.

Campbell BT, Chee PW, Lubbers E, et al. Genetic improvement of the Pee Dee cotton germplasm collection following seventy years of plant breeding. Crop Sci. 2011;51:955–68. https://doi.org/10.2135/cropsci2010.09.0545.

Campbell BT, Myers GO. Quantitative genetics. Cotton. Agronomy monograph. Madison, WI, USA: ASA, CSSA, SSSA; 2015. p. 187–204. https://doi.org/10.2134/agronmonogr57.2013.0024.

Clement JD, Constable GA, Stiller WN, Liu SM. Negative associations still exist between yield and fibre quality in cotton breeding programs in Australia and USA. Field Crops Res. 2012;128:1–7. https://doi.org/10.1016/j.fcr.2011.12.002.

Clement JD, Constable GA, Liu SM. Increasing cotton seed fibre density as a breeding strategy to improve fibre fineness. Field Crops Res. 2014;160:81–9. https://doi.org/10.1016/j.fcr.2014.01.005.

Conaty WC, Constable GA. Factors responsible for yield improvement in new *Gossypium hirsutum* L. cotton cultivars. Field Crops Res. 2020;250:107780. https://doi.org/10.1016/j.fcr.2020.107780.

Constable G, Koebernick JC, Llewellyn D, Walford SA. Cotton breeding for fiber quality improvement. In: Cruz VMV, Dierig DA, editors. Industrial crops: Breeding for bioenergy and bioproducts. New York: Springer; 2015. 191–232. https://doi.org/10.1007/978-1-4939-1447-0_10.

Coyle GG, Smith CW. Combining ability for within-boll yield components in cotton, *Gossypium hirsutum* L. Crop Sci. 1997;37:1118–22.

Culp TW, Harrell DC. Breeding methods for improving yield and fibre quality of upland cotton (*Gossypium hirsutum* L.). Crop Sci. 1973;13:686–9.

Delhom CD, Hequet EF, Kelly B, et al. Calibration of HVI cotton elongation measurements. J Cotton Res. 2020;3:31. https://doi.org/10.1186/s42397-020-00073-1.

Dowd MK, Pelitire SM, Delhom CD. Seed-fiber ratio, seed index, and seed tissue and compositional properties of current cotton cultivars. J Cotton Sci. 2018;22:60–74.

Faulkner WB, Hequet EF, Wanjura J, Boman R. Relationships of cotton fiber properties to ring-spun yarn quality on selected High Plains cottons. Textile Res J. 2012;82:400–14. https://doi.org/10.1177/0040517511426613.

Foulk J, Meredith JWR, McAlister D, Luke D. Fibre and yarn properties improve with new cotton cultivar. J Cotton Sci. 2009;13:212–20.

Ghosh A, Ishtiaque S, Rengasamy S, et al. Predicitive models for strength of spun yarns: an overview. AUTEX Res J. 2005;5:20–9.

Green CC, Culp TW. Simultaneous improvement of yield, fiber quality, and yarn strength in upland cotton. Crop Sci. 1990;30:66–9.

Hafez OMA. Yarn-strength prediction of American cottons. Textile Res J. 1987;48:701–5.

International Cotton Advisory Committee, International Textile Manufacturers Federation. Guideline for standardized instrument testing of cotton. Drieling A, Gourlot J-P, Knowlton J, editors. Amsterdam, Netherlands: ICAC, ITMF; 2018. 45 .

Kelly CM, Osorio-Marin J, Kothari N, et al. Genetic improvement in cotton fiber elongation can impact yarn quality. Ind Crops Prod. 2019;129:1–9. https://doi.org/10.1016/j.indcrop.2018.11.066.

Kelly B, Abidi N, Ethridge D, Hequet EF. Fiber to fabric. Cotton. Agronomy monograph. Madison, WI, USA: ASA, CSSA, SSSA; 2015. p. 665–744. https://doi.org/10.2134/agronmonogr57.2013.0031

Koebernick JC, Liu S, Constable GA, Stiller WN. Parental selection strategy for improving fibre strength and maintaining lint yield in cotton. Ind Crops Prod. 2019;129:585–93. https://doi.org/10.1016/j.indcrop.2018.12.040.

Kuraparthy V, Bowman DT. Gains in breeding upland cotton for fibre quality. J Cotton Sci. 2013;17:157–62.

Liu G, Gordon SG, Yang S, Constable G. Meeting growing demand for high quality cotton from Chinese mills. The Australian Cottongrower. 2010;31:40–3.
Liu G, Yang YR, Wang MK, et al. Comprehensive characterization model of integrated cotton fiber quality index. J Donghua University (English Ed). 2011;28:379–83.
Liu SM, Constable GA, Cullis BR, et al. Benefit of spatial analysis for furrow irrigated cotton breeding trials. Euphytica. 2015;201:253–64. https://doi.org/10.1007/s10681-014-1205-2.
Liu Y, Todd Campbell B, Delhom C. Study to relate mini-spun yarn tenacity with cotton fiber strength. Textile Res J. 2019;89:4491–501. https://doi.org/10.1177/0040517519837725.
Long RL, Bange MP, Gordon SG, et al. Fiber quality and textile performance of some Australian cotton genotypes. Crop Sci. 2010;50:1509–18. https://doi.org/10.2135/cropsci2009.10.0600.
Lord E. The characteristics of raw cotton. In: Coulson AFW, Tordoff M, editors. Manual of cotton spinning, Vol. 2 Part 1. Manchester, UK: The Textile Institute; 1961. p 311–5.
Majumdar A, Majumdar PK, Sarkar B. Determination of technological value of cotton fibre: A comparative study between traditional and multiple criteria decision making approach. AUTEX Res J. 2005;5:71–80.
Mathangadeera RW, Hequet EF, Kelly B, et al. Importance of cotton fiber elongation in fiber processing. Ind Crops Prod. 2020;147:112217. https://doi.org/10.1016/j.indcrop.2020.112217.
May OL, Taylor RA. Breeding cottons with higher yarn tenacity. Textile Res J. 1998;68:302–7. https://doi.org/10.1177/004051759806800409.
Meredith WR, Culp TW, Robert KQ, et al. Determining future cotton variety fiber quality objectives. Textile Res J. 1991;61(12):715–20. https://doi.org/10.1177/004051759106101203.
Meredith WR Jr, Boykin DL, Bourland FM, et al. Genotype × environment inteactions over seven years for yield, yield components, fibre quality, and gosspol traits in the regional high quality tests. J Cotton Sci. 2012;16:160–9.
R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. 2022. https://www.R-project.org/. Accessed 2 Sept 2023.
Ramesh MC, Rajamanickam R, Jayaraman J. The prediction of yarn tensile properties by using artifical neural networks. J Textile Institute. 2008;86:459–68.
Ramey HH, Lawson RJ, Worley JS. Relationship of cotton fibre properties to yarn tenacity. Textile Res J. 1977;47(10):685–91.
Reid P. Sicot 71. Plant Var J. 2003;16:35–6.
Reid P. Sicot F-1. Plant Var J. 2005a;18:84–8.
Reid P. Siokra 24. Plant Var J. 2005b;18:89–92.
Smith AB, Cullis BR, Thompson R. The analysis of crop cultivar breeding and evaluation trials: An overview of current mixed model approaches. J Agric Sci Cambridge. 2005;143:449–62.
Snider JL, Collins GD, Whitaker J, et al. Seed size and oil content are key determinants of seedling vigor in *Gossypium hirsutum*. J Cotton Sci. 2014;18:1–9.
Soil Survey Staff. Keys to soil taxonomy. 7th ed. Washington DC: Natural Resources Conservation Service of USDA; 1996. p. 644.
Stiller W. Sicot 75. Plant Var J. 2008;21:190–3.
Ureyen ME, Kadoglu H. Regressional estimation of ring cotton yarn properties from HVI fibre properties. Textile Res J. 2006;76:360–6.
Ward WT, McTainsh G, McGarry RC, Smith KJ. The soils of the Agricultural Research Station at 'Myall Vale', near Narrabri, NSW, with data analysis using fuzzy k-means. Melbourne: CSIRO Land and Water; 1999.
Yang S, Gordon SG. Accurate prediction of cotton ring-spun yarn quality from high-volume instrument and mill processing data. Textile Res J. 2016;87:1025–39.