Application of GGE Biplot in Analyzing High Yield, Stability, and Adaptability of Upland Cotton: A Case Study of the Nationally Approved New Variety 'Eza Mian 30' in the Yangtze River Valley Cotton Region (Postprint)

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Abstract

High and stable yield together with wide adaptability have always been the primary objectives in crop yield breeding, while the ubiquitous genotype-by-environment interaction effects in multi-environment trials of crop varieties increase the difficulty of breeding for wide adaptability. Scientific evaluation of variety performance in terms of high yield, stability, and adaptability helps improve the efficiency of breeding and application of new varieties. This study employed GGEbiplot® software to analyze the yield performance, stability, and adaptability of tested varieties including 'Ezamian 30' in the 2012–2013 National Cotton Variety Regional Trials in the Yangtze River Valley, and used the "pairwise comparison" function diagram to compare the adaptability performance of 'Ezamian 30' with the control variety 'Ezamian 10' in the target region. The results showed that: 1) 'Ezamian 30' demonstrated outstanding yield performance and excellent stability in the two-year multi-environment variety trials. 2) The comprehensive performance of high yield and stability (i.e., ideal index) of 'Ezamian 30' in the two-year regional trials was significantly superior to the control variety 'Ezamian 10' and all other tested varieties. 3) 'Ezamian 30' was the most widely adaptable variety among all tested varieties, with its most suitable planting area covering most cotton-growing regions in the Yangtze River Valley. 4) 'Ezamian 30' exhibited greater yield advantages than the control variety in the vast majority of cotton-growing regions in the Yangtze River Valley, and was also superior to other tested varieties, demonstrating obvious planting advantages in the Yangtze River Valley cotton region. This study demonstrated the application effectiveness of GGE biplot in analyzing yield performance and stability of varieties and delineating suitable planting regions, and confirmed that 'Ezamian 30' is an ideal variety combining high yield, stability, and wide adaptability, which can provide a theoretical basis for the rational utilization of 'Ezamian 30', and also provides a reference method for comprehensive evaluation of other crop varieties.

Full Text

Evaluation of Upland Cotton Yield Stability and Adaptability Using GGE-Biplot Analysis: A Case Study of 'Ezamian 30' Cotton Cultivar in Yangtze River Valley

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Abstract: High yield, stability, and wide adaptability have always been the primary objectives of crop breeding programs. However, genotype-by-environment interaction (GEI) effects, which are ubiquitous in multi-environment trials of crop varieties, increase the difficulty of breeding for broad adaptability. Scientific evaluation of yield stability and adaptability can improve the efficiency of cultivar development and utilization. This study employed GGEbiplot® software to analyze the yield performance, stability, and adaptability of candidate cultivars including 'Ezamian 30' in the national cotton regional trials of the Yangtze River Valley (YRV) from 2012 to 2013. The "Pairwise Comparison" function was used to compare the adaptive performance of 'Ezamian 30' with the control cultivar 'Ezamian 10' across target regions. The results demonstrated that: (1) 'Ezamian 30' exhibited outstanding yield performance and excellent stability across the two-year multi-environment trials; (2) The integrated performance (i.e., ideal index) of 'Ezamian 30' in combined evaluation of high yield and stability was significantly superior to that of the control 'Ezamian 10' and all other candidate cultivars; (3) 'Ezamian 30' showed the widest adaptability among all tested cultivars, with its optimal planting region covering most cotton-producing areas in the YRV; and (4) 'Ezamian 30' demonstrated greater yield advantage over the control cultivar in the vast majority of YRV cotton regions, while also outperforming other candidate cultivars, indicating clear planting advantages in the YRV cotton zone. This study demonstrates the effectiveness of GGE biplot in concurrently evaluating yield performance and stability, delineating suitable planting regions, and other applications. It confirms 'Ezamian 30' as an ideal cultivar combining high yield, stability, and broad adaptability, providing theoretical guidance for its rational utilization and offering a reference methodology for comprehensive evaluation of other crop varieties.

Keywords: Cotton (Gossypium hirsutum L.); GGE-biplot; Yield stability; Productivity; Adaptability; Regional crop trial

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1.1 Data Sources

The study utilized lint yield data from the national cotton regional trials in the Yangtze River Valley (YRV) for the hybrid insect-resistant cotton cultivar 'Ezamian 30' and its trial group during 2012–2013. In 2012, ten cultivars were evaluated, while eight cultivars were tested in 2013, with 'Ezamian 10' serving as the control cultivar in both years (Table 1). The 2012 trials were conducted at 18 locations: Jianyang (JY) and Shehong (SH) in Sichuan Province; Jingzhou (JZ), Jiangling (JL), Xiangyang (XY), Wuhan (WH), and Huanggang (HG) in Hubei Province; Changde (CD), Datonghu (DTH), and Yueyang (YY) in Hunan Province; Nanyang (NY) in Henan Province; Jiujiang (JJ) in Jiangxi Province; Anqing (AQ) and Hefei (HF) in Anhui Province; Nanjing (NJ), Yancheng (YC), and Nantong (NT) in Jiangsu Province; and Cixi (CX) in Zhejiang Province. All locations successfully completed field experiments according to the trial protocol. In 2013, the Jianli (DY) site in Hubei Province was added, while trials at Jiangling, Datonghu, and Changde were abandoned due to drought, resulting in 16 completed locations. Geographic information including longitude, latitude, altitude, and cotton zone for each location was reported previously [18]. All trials employed a randomized complete block design with three replications and a plot size of 20 m^2.

1.2 Statistical Analysis Methods

First, the "Mean vs. Stability" view [25] in GGEbiplot® software [24] was used to compare yield performance and stability among cultivars. In this view, the small circle represents the "average environment" (the centroid of all test locations) (Figure 1 [Figure 1: see original paper]). The arrowed line passing through the biplot origin and the average environment coordinate is termed the average environment axis (AEA), with its positive direction indicating higher average yield. The perpendicular projection of a cultivar' s icon onto the AEA reflects its yield performance—cultivars closer to the positive direction exhibit better productivity [15,26]. The double-arrowed line perpendicular to the AEA and passing through the origin is the average environment coordinate (AEC) axis; deviation from the AEA in the direction of the arrow indicates yield instability, with proximity to the AEA signifying greater stability [27]. The projection distance of a cultivar vector onto the AEC axis is defined as the stability index, where smaller values indicate better stability.

Second, the "Ideal Cultivar" view [5,25] in GGE biplot was employed for simultaneous selection of yield performance and stability. An "ideal cultivar" is a virtual cultivar positioned on the positive direction of the AEA at a distance from the origin equal to the longest cultivar vector, representing the most desirable combination of high yield and stability [16,25]. The relative distance between each tested cultivar and the ideal cultivar is termed the ideal index, with smaller values indicating better overall performance. Concentric circles centered on the ideal cultivar were drawn to visually assess cultivar ideality [16].

Third, the "Which-Won-Where" view [16,25] was used to delineate suitable planting regions for each cultivar. In the GGE biplot, connecting the outermost cultivar icons forms a polygon encompassing all cultivars. Perpendicular lines drawn from the origin to each polygon side partition the biplot into sectors, where environments within the same sector constitute an environment group. The cultivar at the polygon vertex within each sector is the "winning cultivar" that performs best in those environments, and the production region represented by those test environments represents the most suitable planting area for that cultivar [25].

Finally, the "Pairwise Comparison" view [16] was utilized to compare the advantageous planting regions of 'Ezamian 30' versus the control 'Ezamian 10' across target environments. In the GGE biplot, directly connecting two cultivar icons and drawing a perpendicular line from the origin to this connecting line (or its extension) creates an "iso-performance line." In any environment falling on this line, the two cultivars perform equally. A cultivar performs better in environments located on its side of the iso-performance line. When both cultivars lie on the same side of the line, the cultivar farther from the line performs better in environments on that side, while the nearer cultivar performs better on the opposite side [25].

2.1 Analysis of Variance for Lint Yield

Combined analysis of variance for cotton lint yield across the 2012–2013 YRV national trials revealed that genotype (G), environment (E), and genotype-by-environment interaction (GE) effects were all highly significant sources of phenotypic variation (Table 2). In 2012, genotype, environment, and GE interaction accounted for 6.2%, 85.6%, and 8.2% of total treatment variation, respectively. In 2013, these proportions were 10.9%, 70.7%, and 18.4%, respectively. Environment was the primary source of variation in lint yield, but this effect is irrelevant for genotype evaluation. The GGE model effectively removes environmental effects to enable scientific assessment of genotypes. Moreover, the contribution of GE interaction to treatment variation exceeded that of genotype main effects in both years, necessitating further analysis of GE interaction to scientifically delineate suitable planting regions for each cultivar.

2.2 Yield Performance and Stability Analysis of 'Ezamian 30'

Multiple comparison of yield differences among cultivars in the 2012–2013 YRV trials (LSD test) showed that 'Ezamian 30' produced significantly higher lint yield than the control 'Ezamian 10' and all other cultivars in both years (Table 1). The "Mean vs. Stability" view of GGE biplot was used to evaluate cultivar productivity (Figure 1). In 2012, cultivar ranking for yield performance was: 'Ezamian 30' (Ezm30) > 'Ezamian 10' (Ezm10) > 'Siyang 839' (Sy839) > 'Datang 6' (Dt6) > 'Jiuzamian 11' (Jzm11) > 'Fengtianmian 1' (Ftm1) > 'Zhongmiansuo 61' (Zms61) > 'Xiangzamian 23' (Xzm23) > 'Qimian 8' (Qm8) > 'Jinkemian 8' (Jkm8). The perpendicular projection of 'Ezamian 30' onto the

AEA was closest to the positive direction and far from other cultivars, indicating superior productivity that aligned with multiple comparison results. In 2013, the yield ranking was: 'Ezamian 30' (Ezm30) > 'Rihuimian 10' (Rhm10) > 'Quanyinmian 8' (Qym8) > 'Ezamian 10' (Ezm10) > 'Ningkangmian 2' (Nkm2) > 'GK39' > 'Chuangmian 11' (Cm11) > 'Xumian 21' (Xm21), with 'Ezamian 30' again showing clear yield superiority.

Stability analysis for 2012 (Figure 1a, Table 1) indicated that 'Ezamian 10' and 'Ezamian 30' had the shortest projection distances on the AEC axis and the lowest stability indices, demonstrating the best stability. 'Siyang 839', 'Jiuzamian 11', 'Fengtianmian 1', 'Qimian 8', and 'Jinkemian 8' showed moderate stability, while 'Xiangzamian 23' and 'Datang 6' exhibited poor stability, and 'Zhongmiansuo 61' had the poorest stability with the longest projection distance. In 2013 (Figure 1b, Table 1), 'Ezamian 10' fell directly on the AEA with a stability index of zero, showing perfect stability. 'Ezamian 30', 'Rihuimian 10', and 'Quanyinmian 8' demonstrated excellent stability, 'Xumian 21' showed good stability, while 'Ningkangmian 2' and 'GK39' exhibited poor stability. These results confirm that 'Ezamian 30' combined outstanding yield performance with excellent stability across both years.

2.3 Ideal Index Analysis of 'Ezamian 30'

The ideal cultivar in GGE biplot is a virtual cultivar with the longest vector positioned on the positive direction of the AEA, representing optimal high-yield stability. Serving as a reference for comprehensive evaluation, the relative distance between each cultivar and the ideal cultivar is termed the ideal index, where smaller values indicate better overall performance. In 2012 (Figure 2a, Table 1), 'Ezamian 30' was closest to the ideal cultivar with an ideal index approaching zero, indicating the best combined performance of yield and stability. 'Ezamian 10' and 'Siyang 839' were relatively ideal, while 'Fengtianmian 1', 'Jiuzamian 11', and 'Datang 6' showed moderate performance. 'Zhongmiansuo 61', 'Qimian 8', and 'Xiangzamian 23' performed poorly, and 'Jinkemian 8' showed the poorest performance. In 2013 (Figure 2b, Table 1), 'Ezamian 30' again exhibited the best ideal index with its icon very close to the ideal cultivar, demonstrating excellent combined performance. 'Rihuimian 10', 'Quanyinmian 8', and 'Ezamian 10' also showed relatively ideal performance, while 'Ningkangmian 2', 'Chuangmian 11', 'GK39', and 'Xumian 21' had poor ideal indices. Thus, 'Ezamian 30' significantly outperformed the control 'Ezamian 10' and all other cultivars in combined high-yield stability across both years.

2.4 Suitable Planting Region Delineation for 'Ezamian 30'

In GGE biplot, perpendicular lines from the origin to the sides of a polygon formed by connecting outermost cultivar icons partition the target region into sectors. The cultivar at each polygon vertex is the "winning cultivar" that performs best in the environments within that sector, and the production region represented by those test environments constitutes the most suitable planting area for that cultivar. Figure 3a [Figure 3: see original paper] shows that in 2012, winning cultivars at polygon vertices included 'Ezamian 30', 'Datang 6', 'Zhongmiansuo 61', 'Jinkemian 8', and 'Xiangzamian 23'. 'Datang 6' was optimal for Anqing (Anhui) and Yueyang (Hunan) environments. 'Ezamian 30' covered all target environments in both upper and lower YRV cotton zones, plus most middle YRV zones except Anqing and Yueyang, representing the main cotton-producing region and indicating the broadest adaptability among all cultivars. The remaining winning cultivars did not include any test environments in their sectors, suggesting they were unsuitable for YRV cotton production.

Figure 3b shows that in 2013, winning cultivars included 'Ezamian 30', 'Ningkangmian 2', 'GK39', and 'Xumian 21'. 'Ningkangmian 2' was optimal for Jiujiang (Jiangxi) and Jianyang (Sichuan); 'GK39' for Cixi (Zhejiang); while 'Ezamian 30' was optimal for the remaining 13 locations representing most YRV cotton zones, again showing the widest adaptability. These results demonstrate that 'Ezamian 30' was the most broadly adapted cultivar among all candidates, with its optimal planting region encompassing the vast majority of YRV cotton zones.

2.5 Comparison of Advantageous Planting Regions Between 'Ezamian 30' and 'Ezamian 10'

The pairwise comparison view of GGE biplot enables direct comparison of advantageous planting regions between two cultivars. Figure 4a [Figure 4: see original paper] shows that in 2012, both 'Ezamian 30' and 'Ezamian 10' icons were located on the right side of the iso-performance line, as were all test environment icons. Since 'Ezamian 30' was farther from the iso-performance line, it outperformed 'Ezamian 10' in all test environments, indicating its advantage covered the entire YRV cotton zone. Figure 4b shows that in 2013, both cultivars again fell on the right side of the iso-performance line, with only the Cixi location on the left side. This indicates 'Ezamian 10' was superior only in the coastal cotton region of Cixi, Zhejiang, while 'Ezamian 30' performed better in all other target regions, demonstrating broader adaptability. Thus, 'Ezamian 30' showed clear yield advantage over the control cultivar and other candidates across most YRV cotton zones, confirming its strong regional planting advantage.

3.1 Necessity of Simultaneous Evaluation of High Yield and Stability in Cotton Varieties

In multi-environment variety trials, yield performance is jointly influenced by genotype, environment, and GEI effects, with environment being the primary source of variation and GEI contribution typically exceeding genotype main effects [28]. GEI is the key factor affecting variety stability and adaptability, and only through thorough investigation and utilization of repeatable GEI effects can breeding efficiency for stability be improved [29]. AMMI and GGE biplot analyses are currently the most common statistical methods for GEI analysis.

AMMI first partitions additive main effects through traditional ANOVA, then decomposes interaction effects in residuals via principal component analysis, effectively analyzing GEI and stability [30]. However, AMMI neglects yield performance, and abstract discussion of stability without considering productivity is meaningless for both breeding and production applications [14]. Simultaneous evaluation and integrated selection for both yield performance and stability are essential.

The GGE biplot model proposed by Yan et al. [12] combines genotype main effects with GEI, visually displaying both yield performance and stability to facilitate simultaneous evaluation and selection, making it the most practical and effective statistical method for comprehensive assessment of high-yield stability. This study applied GGE biplot' s "Mean vs. Stability" and "Ideal Cultivar" views to analyze yield performance and stability of 'Ezamian 30' and other cultivars in the 2012–2013 YRV trials. The results showed 'Ezamian 30' combined outstanding yield performance with excellent stability, and its ideal index for combined evaluation was significantly superior to the widely adopted control 'Ezamian 10' and all other cultivars, confirming it as an excellent new cultivar with high-yield stability. These findings clarify the yield and stability characteristics of 'Ezamian 30' , providing theoretical guidance for its scientific application and further demonstrating the feasibility and effectiveness of GGE biplot for simultaneous evaluation of cotton cultivar performance.

3.2 Breeding Strategies for Wide vs. Specific Adaptability in New Cotton Varieties

Current cultivar evaluation in China' s regional trials and registration system primarily relies on average performance across multi-environment trials, effectively assuming the target region as a homogeneous mega-environment [26]. If this assumption is invalid, the yield potential of positive GEI effects for specific adaptability cannot be fully exploited. Breeding for broad adaptability across complex target regions with multiple mega-environments is more challenging than breeding for high yield within homogeneous mega-environments [19]. Under such conditions, an effective approach is to partition the target region into several relatively homogeneous mega-environments, then conduct specific-adaptation breeding for each, substantially improving breeding efficiency and cultivar deployment reliability [12].

The YRV cotton region is vast, encompassing upper, middle, and lower reaches across Sichuan, Hunan, Hubei, Henan, Anhui, Jiangxi, Jiangsu, and Zhejiang provinces, with significant variation in natural ecological conditions, soil factors, and meteorological conditions [18]. Under China' s current cultivar registration system that emphasizes broad adaptability evaluation with national and provincial two-tier registration, cotton breeding in the YRV should integrate both broad- and specific-adaptation strategies. Within the framework of the entire YRV target environment, broad-adaptation breeding can select widely adapted "major cultivars" suitable for the whole region, while specific-adaptation breeding should target special mega-environments or utilize provincial trials to select "minor cultivars" with specific adaptations. This approach enables targeted cultivar selection and utilization, maximizing the production benefits of optimal cultivar-environment combinations while avoiding risks from unsuitable combinations.

GGE biplot has been widely applied to mega-environment delineation and suitable planting region identification for various crops [19-21]. This study comprehensively evaluated suitable planting environments for 'Ezamian 30' and other cultivars in the YRV using GGE biplot, and compared yield performance between 'Ezamian 30' and the control cultivar using pairwise comparison. The results showed 'Ezamian 30' exhibited the broadest adaptability to YRV cotton zones in both years, with absolute regional advantage over the control cultivar. These findings establish 'Ezamian 30' as a universally adapted cultivar for the YRV. Combined with its high-yield stability characteristics, 'Ezamian 30' represents a successful example of broad-adaptation breeding for the YRV cotton region, while demonstrating the effectiveness and practicality of GGE biplot' s "Which-Won-Where" function for delineating suitable planting regions.

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Note: Figure translations are in progress. See original paper for figures.