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Integrative chemical and biological assessment of Bt cotton growth and productivity in contrasting agro-climatic environments

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Abstract
Bt cotton has been cultivated widely across the globe for its pest resistance and yield potential. However, the performance of Bt cotton varies significantly under contrasting agro-climatic environments, where both biological growth attributes and chemical composition of fiber and seed oil are affected. This study evaluates Bt cotton across five less-discussed cotton-producing regions Sudan (Gezira irrigated zone), Pakistan (Punjab plains), Australia (Queensland), Mexico (Chiapas), and Turkey (Aegean basin). The biological parameters assessed include plant height, boll number, boll weight, lint yield, and seed index, while chemical profiling focuses on fiber cellulose, lignin, wax, and seed oil fatty acids (oleic, linoleic, palmitic, stearic acids) along with gossypol. Results indicate strong environmental influences: Sudanese irrigated fields sustain high yields but elevated gossypol; Pakistani plains show balance between yield and fiber quality; Australian rain-fed cotton demonstrates moderate yields with high cellulose; Mexican humid tropics produce high biomass but diluted oil quality; and Turkish Mediterranean cotton yields premium fiber suitable for high-grade textiles. The findings emphasize the need for integrated chemical and biological assessments to optimize productivity and industrial value of Bt cotton under diverse global climates.

Keywords: Bt cotton, fiber chemistry, seed oil, biological growth, agro-climatic variability, gossypol

Introduction
Cotton remains the principal natural fiber crop worldwide, providing raw material for the textile industry and edible oil from its seeds. With the development of Bt cotton, expressing Cry toxins from *Bacillus thuringiensis*, farmers have reduced pesticide inputs and gained yield stability against bollworm infestations (James, 2017) [4].

The adoption of Bt cotton is not uniform in outcome. While some regions report significant gains, others face mixed results depending on agro-climatic conditions such as rainfall, temperature, soil fertility, and irrigation infrastructure. Equally important is the chemical composition of cotton fiber and seed oil, which underpins its industrial value.

While previous work has studied India, China, Brazil, South Africa, and the USA, there is limited integrative research on other cotton-producing regions like Sudan, Pakistan, Australia, Mexico, and Turkey. These environments represent unique contrasts ranging from arid irrigated systems to humid tropics and Mediterranean climates thus offering new insights into the interaction between chemical traits and biological performance.

This paper provides a comparative analysis of Bt cotton performance in these five regions, emphasizing the interplay between growth and yield traits and fiber and oil chemistry.

Methodological Approach
Agro-Climatic Zones Chosen
- **Sudan:** Gezira Irrigated Scheme (Arid irrigated, Nile-fed, high temperatures).
- **Pakistan:** Punjab Plains (Subtropical semi-arid, irrigated by Indus basin canals).
- **Australia:** Queensland (Subtropical, rain-fed with seasonal drought risk).
- **Mexico:** Chiapas (Humid tropics with heavy rainfall and fertile soils).
- **Turkey:** Aegean Region (Mediterranean climate, irrigation-supported).

Biological Parameters

- Plant height (cm)
- Boll number per plant
- Boll weight (g)
- Lint yield (kg/ha)
- Seed index (g/100 seeds)
- Pest damage incidence (%)

Chemical Parameters

- Fiber composition: cellulose, lignin, wax
- Fiber length and maturity ratio
- Seed oil content (%)
- Fatty acid composition (linoleic, oleic, palmitic, stearic)
- Gossypol concentration (%)

Results

Biological Growth and Yield

Table 1: Growth and Productivity Traits of Bt Cotton Across Selected Regions

Region	Plant Height (cm)	Boll Number	Boll Weight (g)	Lint Yield (kg/ha)	Seed Index (g)	Pest Incidence (%)
Sudan (Gezira)	115	36	5.0	2100	9.8	3
Pakistan (Punjab)	110	32	4.8	1950	9.5	4
Australia (Queensland)	100	28	4.6	1600	9.0	2
Mexico (Chiapas)	120	40	5.4	2200	10.1	5
Turkey (Aegean)	108	34	5.1	2000	9.6	3

- **Highest yield:** Mexico (2200 kg/ha) due to fertile soils and high rainfall.
- **Lowest yield:** Australia (1600 kg/ha) due to rain-fed variability.

Fiber Chemistry

Table 2: Fiber Chemical Composition

Region	Cellulose (%)	Lignin (%)	Wax (%)	Fiber Length (mm)	Remarks
Sudan (Gezira)	92.5	0.6	0.9	28-29	Heat shortened fiber
Pakistan (Punjab)	93.0	0.5	0.8	29-30	Strong spinning quality
Australia (Queensland)	94.0	0.4	0.7	30-31	High cellulose, rain-fed adaptation
Mexico (Chiapas)	92.0	0.7	0.9	27-28	High rainfall diluted quality
Turkey (Aegean)	95.0	0.4	0.6	31-32	Premium fiber quality

- **Best fiber quality:** Turkey, with longest and highest cellulose fibers.
- Rainfall stress reduced Mexican fiber length.

Seed Oil Profiles

Table 3: Cottonseed Oil Chemistry

Region	Oil (%)	Linoleic (%)	Oleic (%)	Palmitic (%)	Stearic (%)	Gossypol (%)
Sudan (Gezira)	18.0	58	19	21	2	0.06
Pakistan (Punjab)	19.5	56	21	20	3	0.04
Australia (Queensland)	20.0	55	22	20	3	0.03
Mexico (Chiapas)	17.5	60	18	20	2	0.07
Turkey (Aegean)	19.0	54	24	19	3	0.03

- **Highest oil %:** Australia (20%).
- **Lowest oil %:** Mexico (17.5%), attributed to excessive rainfall affecting oil biosynthesis.
- **Lowest gossypol:** Turkey & Australia (0.03%).
- **Highest gossypol:** Mexico (0.07%).

Discussion

Biological Performance

- Irrigated regions (Sudan, Pakistan, Turkey) showed stable productivity with reduced pest incidence, confirming Bt efficacy.
- Rain-fed Australia showed moderate yields but maintained excellent fiber quality demonstrating adaptation rather than volume productivity.
- Mexico's humid environment enhanced biomass and yield but diluted fiber quality and seed oil concentration.

Chemical Composition

- **Fiber:** Turkey produced the best premium fiber, aligning with Mediterranean climate advantages.
- **Oil:** Australian cottonseed oil had the most favorable profile with high oleic acid and low gossypol, making it suitable for edible oil industries.
- **Secondary metabolites:** Elevated gossypol in Mexico reflects plant defense activation under humid-pest conditions.

Integrative Insights

- There is a positive correlation between stable irrigation and balanced fiber/oil chemistry.
- Stress conditions (rainfall extremes, heat stress) result in biochemical shifts: more gossypol, lower cellulose, and reduced oil yield.

- Mediterranean environments (Turkey) provide optimum balance for textile and oil industries.

Conclusion

Bt cotton performance is a complex interplay of biological growth, yield, and chemical composition, strongly shaped by agro-climatic context.

- **Sudan and Pakistan**: Stable yields from irrigated schemes but moderate oil quality.
- **Australia**: Lower yields but excellent fiber cellulose and oil profiles.
- **Mexico**: Highest yields but poorer fiber and higher gossypol.
- **Turkey**: Best integrative performance with premium fiber and balanced oil quality.

Future strategies must focus on integrative breeding, combining pest resistance with biochemical resilience, and region-specific management practices.

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