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# Simulation-Based Investigation of Locally Available Natural Materials as Dielectric Substrates for Microstrip Patch Antennas

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**Abstract:** This research presents a simulation-based performance investigation of a 5.8 GHz microstrip patch antenna using locally available natural materials as dielectric substrates. Natural substrates, including Bamboo, Wood, Paper, Cotton and Palm fiber, were characterized alongside standard FR-4 dielectric material. The analytical framework evaluated fundamental dielectric parameters, including relative permittivity ($\varepsilon_r$), loss tangent (tan δ), imaginary permittivity ($\varepsilon''$) and effective permittivity ($\varepsilon_{eff}$), revealing an inverse relationship between $\varepsilon_r$ and required patch footprint (ranging from 15.798 mm × 11.803 mm for FR-4 up to 22.683 mm × 19.139 mm for Cotton). Closed-form transmission line equations produced an initial analytical frequency offset of 9.58% to 12.28% above the 5.8 GHz target, necessitating numerical co-optimization in CST Studio Suite. Benchmark validation of custom FR-4 ($\varepsilon_r$ = 4.36, tan δ = 0.01) against CST's built-in library model confirmed numerical model fidelity across 4–7 GHz. Full-wave CST simulations demonstrated that Cotton ($\varepsilon_r$ = 1.6, tan δ = 0.0015) achieved superior performance with the highest radiation efficiency (67.0%) and peak gain (3.66 dBi), outperforming all other natural dielectrics. Wood and Palm fiber provided strong impedance matching ($S_{11}$ = −35.31 dB and −33.36 dB; VSWR = 1.35 and 1.13) with moderate efficiencies (45.8% and 41.2%). Paper exhibited the highest attenuation (tan δ = 0.04), yielding the lowest radiation efficiency (29.8%) and peak gain (1.45 dBi). These findings establish the viability of natural dielectrics for eco-friendly wireless systems while delineating key physical trade-offs in substrate loss and antenna geometry.

**Keywords:** Microstrip patch antenna, Natural dielectric substrate, 5.8 GHz ISM band,CST Studio Suite,Radiation efficiency, Eco-friendly antenna

## 1. INTRODUCTION

The expansion of modern wireless communications has driven continuous demand for compact, efficient, low-cost and environmentally sustainable antenna systems. Microstrip patch antennas are widely utilized in Industrial, Scientific and Medical (ISM) band applications, such as 5.8 GHz Wi-Fi, RFID and wireless sensor nodes, due to their low profile, light weight and ease of integration with planar microwave integrated circuits. The performance of a microstrip patch antenna is fundamentally dictated by the physical and electromagnetic properties of its underlying dielectric substrate, primarily its relative permittivity (εr) and loss tangent (tan δ). Conventional substrates such as Flame Retardant 4 (FR-4) are commercially favored for their low cost and structural rigidity. However, FR-4 exhibits high dielectric losses (tan δ ≌ 0.01 to 0.02) and frequency-dependent behavior at microwave frequencies, leading to power dissipation, low radiation efficiency and potential thermal stability issues. Moreover, synthetic substrate manufacturing raises long-term environmental concerns regarding non-biodegradable electronic waste.To address these economic and environmental

 

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challenges, recent research has explored alternative, eco-friendly and locally available organic dielectrics. Natural materials, such as wood, paper, bamboo, cotton, and agricultural fibers, offer low production costs, abundance and biodegradability. Despite these advantages, comprehensive studies evaluating minimally processed or indigenous natural substrates for 5.8 GHz antenna applications require rigorous numerical modeling to overcome limitations in analytical design formulations.This study presents a comparative performance evaluation of five candidate natural eco-friendly substrates (Bamboo, Wood, Paper, Cotton, and Palm fiber) against standard FR-4 at 5.8 GHz. Using a two-tier framework comprising analytical screening in MATLAB and full-wave 3D electromagnetic simulation in CST Studio Suite, this paper validates CST simulation methodology against built-in library benchmarks and quantifies the physical trade-offs in gain, impedance matching, bandwidth, and radiation efficiency to establish the feasibility of natural dielectrics in modern antenna engineering.

## 2. LITERATURE REVIEW

Microstrip patch antenna design relies heavily on optimizing substrate properties to balance physical dimensions, radiation efficiency and operating bandwidth. As established in classical electromagnetic theory (Balanis, 2016; Pozar, 2012), lower relative permittivity (εr) expands the fringing fields, enhancing fringe radiation and increasing overall radiation efficiency and bandwidth. Higher permittivity substrates confine fields within the dielectric layer, reducing antenna dimensions at the expense of narrowed bandwidth and elevated surface-wave losses. Furthermore, Garg et al. (2001) emphasized that the substrate loss tangent (tan δ) governs internal dielectric dissipation, directly constraining total antenna efficiency. Recent literature highlights a clear shift toward eco-friendly, flexible and bio-composite substrate alternatives. Ahmad et al. (2020) and Ramesh et al. (2018) characterized natural fiber composites, demonstrating that bio-based materials can yield stable dielectric constants suitable for microwave frequencies. Salonen and Rahmat-Samii (2007) successfully applied textile and paper substrates to flexible, wearable antennas, confirming that natural organic fibers can support effective impedance matching. Similarly, Sreekala et al. (2002) investigated oil palm fiber composites, noting that proper surface treatment and moisture mitigation are essential for maintaining stable dielectric loss tangents. In high-frequency comparative literature, Thompson and Lee (2024) and Martinez et al. (2023) evaluated synthetic microwave laminates against FR-4, observing that high loss tangents in FR-4 induce artificial bandwidth broadening due to severe Q-factor degradation. While engineered materials such as Rogers RT/duroid 5880 deliver optimal radiation efficiency, their high cost impedes deployment in cost-sensitive or single-use wireless sensor nodes. Closed-form transmission line models often underpredict fringing capacitance effects in lower-permittivity regime substrates, introducing frequency offsets relative to target operating bands. This study bridges that gap by systematically evaluating locally available natural dielectrics under standardized numerical conditions using validated CST Studio Suite models.

## 3. METHODOLOGY

The research adopted a two-tier simulation-based comparative framework consisting of preliminary analytical dielectric screening followed by full-wave 3D electromagnetic simulation and validation in CST Studio Suite.

### 3.1 Dielectric Characterization and Substrate Screening

Five natural candidate materials (Bamboo, Wood, Paper, Cotton and Palm fiber) were evaluated alongside standard FR-4. The analytical framework evaluated fundamental dielectric parameters, including relative permittivity ($\varepsilon_r$), loss tangent

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(tan δ), imaginary permittivity (ε″ = $\varepsilon_r$ tan δ) and effective permittivity ($\varepsilon_{eff}$). The values of permittivity ($\varepsilon_r$) and loss tangent (tan δ) were obtained by taking the average values of these values obtained over different literature materials at 5.8GHz. Dielectric dissipation performance was screened against a maximum acceptable loss threshold of tan δ = 0.02, with full parameters and screening outcomes summarized in Table 1.

**Table 1. Preliminary Dielectric Screening Results for the Candidate Substrates at 5.8 GHz**

| Material | εr | tan δ | ε″ | εeff | W (mm) | L (mm) | fr,est (GHz) | Freq. error (%) | Screening outcome |
|---|---|---|---|---|---|---|---|---|---|
| FR-4 | 4.36 | 0.0100 | 0.0436 | 3.8087 | 15.798 | 11.803 | 6.5120 | 12.277 | Suitable |
| Bamboo | 2.4 | 0.0300 | 0.0720 | 2.1990 | 19.835 | 15.812 | 6.3974 | 10.299 | Flagged for CST optimization |
| Wood | 2.0 | 0.0200 | 0.0400 | 1.8619 | 21.116 | 17.244 | 6.3748 | 9.9106 | Suitable |
| Paper | 2.8 | 0.0400 | 0.1120 | 2.5327 | 18.762 | 14.679 | 6.4210 | 10.706 | Flagged for CST optimization |
| Cotton | 1.6 | 0.0015 | 0.0024 | 1.5208 | 22.683 | 19.139 | 6.3555 | 9.5772 | Suitable |
| Palm fiber | 2.2 | 0.0250 | 0.0550 | 2.0309 | 20.446 | 16.483 | 6.3859 | 10.101 | Flagged for CST optimization |

Cotton, Wood and FR-4 fell within the acceptable low-loss threshold and were classified as suitable, while Bamboo, Paper and Palm fiber exceeded the tan δ = 0.02 screening limit and were flagged for further numerical co-optimization in CST Studio Suite.

### 3.2 Analytical Dimension Synthesis

Initial physical patch dimensions (width W and length L) were computed using standard microstrip transmission line equations centered at fr = 5.8 GHz:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \quad \textit{equation (1)}$$

$$W = \frac{c}{2f_r\sqrt{\frac{(\varepsilon_r+1)}{2}}} \quad \textit{equation (2)}$$

$$L = \frac{C}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \quad \textit{equation (3)}$$

Analytical closed-form equations yielded estimated resonant frequencies (fr) ranging from 6.3555 GHz (Cotton) to 6.5120 GHz (FR-4), representing an initial frequency offset of 9.58% to 12.28% above the 5.8 GHz design target due to un-modeled fringing capacitance in low-εr regimes.

### *3.3 CST Benchmarking and Full-Wave Simulation*

To establish simulation fidelity, a benchmarking validation was conducted in CST Studio Suite by comparing a microstrip patch antenna on customized FR-4 ($\varepsilon_r$ = 4.36, tan δ = 0.01) against a control model using CST's standard built-in FR-4 library material. Both models demonstrated synchronized resonance at 5.8 GHz across the 4–7 GHz band, as shown in Figure 1. Minor variances in $S_{11}$ notch depth (−19 dB for customized FR-4 vs. −32 dB for built-in FR-4) were attributed to dispersion models (e.g., Djordjevic–Sarkar fits) in the library definition versus constant baseline inputs. Full 3D transient solver simulations were then executed for all five natural substrates to evaluate $S_{11}$ reflection coefficients, Voltage Standing Wave Ratio (VSWR), −10 dB bandwidth, radiation efficiency, peak gain and H-field radiation patterns at 5.8 GHz.

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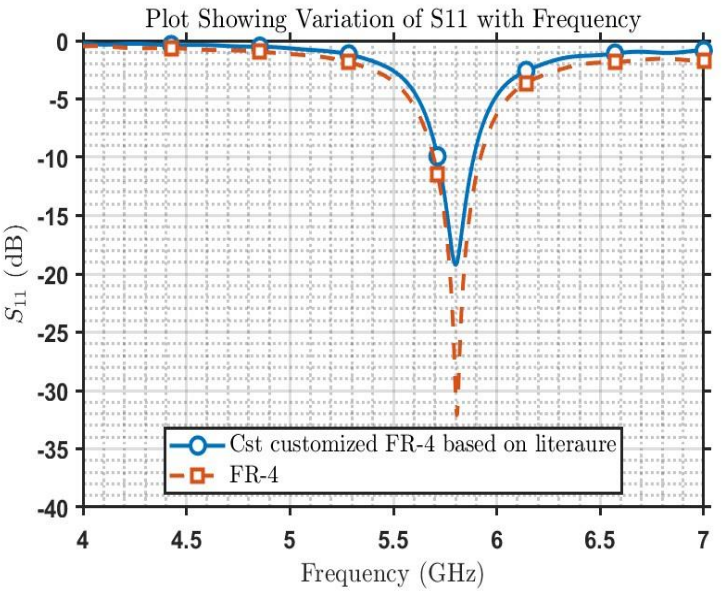


**Figure 1. Validation of the CST Customized FR-4 Model Against the Built-in Library FR-4 Benchmark**

## 4. RESULTS AND DISCUSSION

The numerical performance results obtained from full-wave CST Studio Suite simulations for all studied natural substrates are summarized in Table 2.

**Table 2. CST Experimental Simulation Results for the Studied Substrates at 5.8 GHz**

| Substrate | Patch area ($mm^2$) | S11 (dB) | Bandwidth (MHz) | Radiation efficiency (%) | Peak gain (dBi) | VSWR |
|---|---|---|---|---|---|---|
| Cotton | 22.68 × 19.50 | -15.85 | 155 | 67.0 | 3.66 | 1.380 |
| Wood | 21.16 × 17.24 | -35.31 | 230 | 45.8 | 2.41 | 1.350 |
| Palm fiber | 20.45 × 16.70 | -33.36 | 240 | 41.2 | 2.12 | 1.130 |
| Bamboo | 19.835 × 15.812 | -25.48 | 245 | 36.8 | 1.85 | 1.197 |
| Paper | 18.76 × 14.67 | -22.01 | 274 | 29.8 | 1.45 | 1.204 |

### 4.1 Geometry and Permittivity Dependence

A clear inverse relationship was confirmed between relative permittivity ($\varepsilon_r$) and physical patch dimensions. FR-4, having the highest permittivity ($\varepsilon_r = 4.36$), yielded the highest effective dielectric constant ($\varepsilon_{eff} = 3.8087$) and required the smallest physical footprint (15.798 mm × 11.803 mm). Conversely, natural organic substrates required larger physical structures due to lower permittivity levels:

- Cotton ($\varepsilon r = 1.6$): 22.68 mm × 19.50 mm (442.26 $mm^2$)
- Wood ($\varepsilon r = 3.2$): 21.16 mm × 17.24 mm (364.80 $mm^2$)
- Palm Fiber ($\varepsilon r = 4.0$): 20.45 mm × 16.70 mm (341.52 $mm^2$)
- Bamboo ($\varepsilon r = 2.8$): 19.835 mm × 15.812 mm (313.63 $mm^2$)
- Paper ($\varepsilon r = 2.8$): 18.76 mm × 14.67 mm (275.21 $mm^2$)

Lower relative permittivity values decrease phase velocity retardation and expand fringing fields, demanding physically larger patch dimensions to achieve electromagnetic resonance at 5.8 GHz.

### 4.2 Impedance Matching, Bandwidth and Radiation Performance

All five natural substrates achieved excellent impedance matching at 5.8 GHz, comfortably surpassing the standard S11

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≤ −10 dB and VSWR ≤ 2.0 thresholds as illustrated in Figures 2 and 3.

- Wood and Palm Fiber demonstrated the deepest return loss peaks at −35.31 dB (VSWR = 1.35) and −33.36 dB (VSWR = 1.13), respectively.
- Bamboo achieved an S11 of −25.48 dB (VSWR = 1.197), Paper reached −22.01 dB (VSWR = 1.204) and Cotton recorded −15.85 dB (VSWR = 1.38).

Bandwidth analysis revealed that substrates with higher loss tangents displayed broader −10 dB impedance bandwidths, ranging from 155 MHz for Cotton up to 274 MHz for Paper. However, this bandwidth expansion in high-loss materials comes at the direct cost of radiation efficiency.

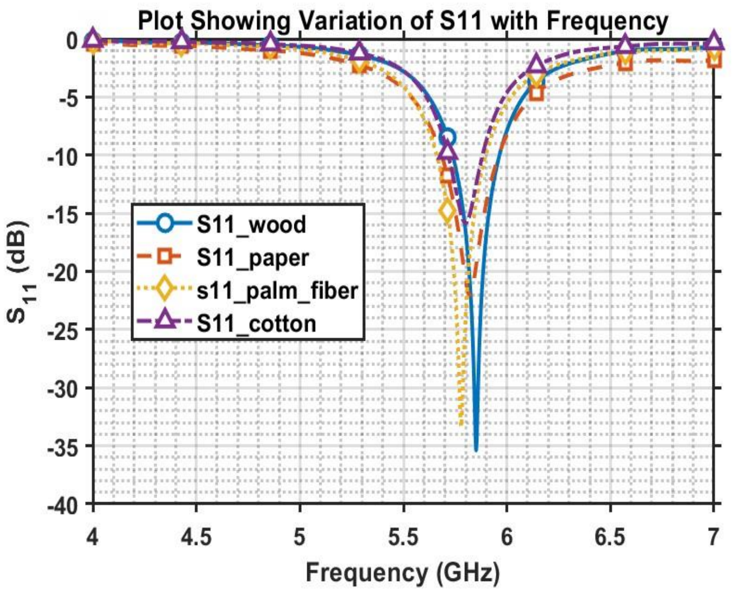


**Figure 2. S11 Reflection Coefficient Results for the Natural Substrates as Obtained in CST**

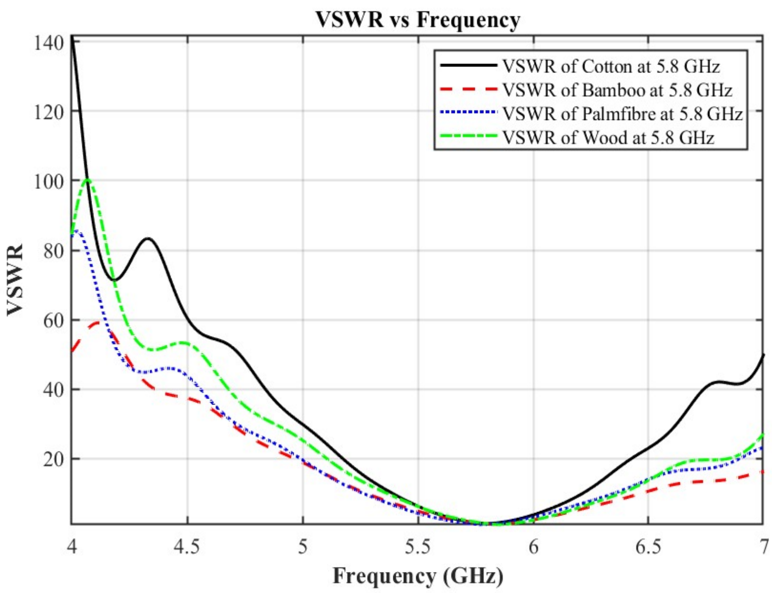


**Figure 3. VSWR versus Frequency Results for the Natural Substrates as Obtained in CST**

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Cotton outperformed all candidate natural substrates in radiation performance, achieving a peak gain of 3.66 dBi and a radiation efficiency of 67.0%. This superior performance directly reflects Cotton's low loss tangent (tan δ = 0.0015, ε″ = 0.0024), which minimizes internal dielectric dissipation. Wood and Palm Fiber delivered moderate radiation efficiencies of 45.8% (2.41 dBi gain) and 41.2% (2.12 dBi gain). Bamboo achieved 36.8% efficiency (1.85 dBi gain), while Paper exhibited the lowest efficiency (29.8%) and peak gain (1.45 dBi) due to its high loss tangent (tan δ = 0.04, ε″ = 0.112).

The H-field radiation patterns recorded across all natural substrates at 5.8 GHz, presented in Figures 4–8, displayed consistent broadside directional radiation characteristics, confirming that substrate dissipation alters total radiated power and gain magnitude without distorting fundamental spatial radiation patterns.

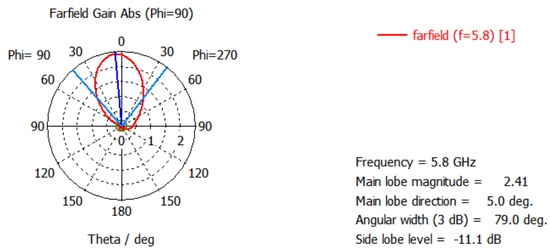


**Figure 4. H-field Radiation Pattern at 5.8 GHz Using Wood Substrate**

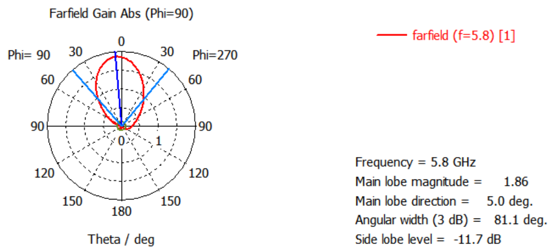


**Figure 5. H-field Radiation Pattern at 5.8 GHz Using Bamboo Substrate**

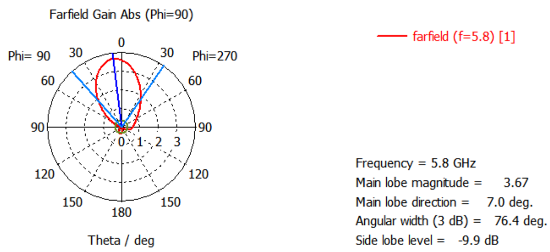


**Figure 6. H-field Radiation Pattern at 5.8 GHz Using Cotton Substrate**

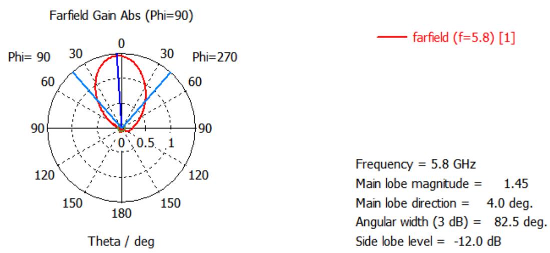


**Figure 7. H-field Radiation Pattern at 5.8 GHz Using Paper Substrate**

 

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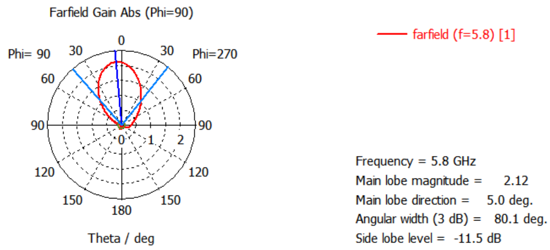


**Figure 8. H-field Radiation Pattern at 5.8 GHz Using Palm Fiber Substrate**

## 5. CONCLUSION

This study demonstrates that natural, eco-friendly materials like Cotton and Wood can serve as effective, low-cost dielectric substrates for 5.8GHz microstrip patch antennas. Full-wave simulations revealed that cotton achieved the highest performance with a 67.0 % radiation efficiency and 3.66 dBi peak gain, significantly outperforming higher-loss organic alternatives like paper and palm fiber. While these findings prove the physical feasibility of bio-based substrates for green wireless technology, practical fabrication must still account for natural fiber anisotropy and moisture sensitivity.

## 6. LIMITATION OF THE STUDY

A notable limitation of this simulation study lies in the sourcing of dielectric properties and the loss tangent ($\epsilon_r$ and tan δ). The constitutive parameters for the natural substrates were established by taking average baseline values from compiled literature at or near 5.8 GHz, rather than through direct empirical characterization (e.g., split-post dielectric resonator or coaxial probe measurements) of specific physical samples. Because natural organic materials exhibit significant batch-to-batch variability due to origin, processing history, density and moisture content, averaged literature figures represent an approximation. Consequently, physical prototypes fabricated from uncharacterized raw samples may exhibit minor resonant frequency offsets and impedance discrepancies relative to the CST simulation results, highlighting the necessity of empirical material characterization prior to hardware production.

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