Microwave Dielectric Sensing of Moisture Content in Shelled Peanuts Independent of Bulk Density and with Temperature Compensation

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Importance of moisture content

- Determines time for harvest
- Determines suitability for storage
- Factor in conditioning for processing
- Factor in price determination

Moisture in granular materials

- Water is an important component in many organic and inorganic materials.
- There is often a need for on-line sensors for real-time determination of moisture content in granular and powdered materials.
- Industries, for example, include food and agriculture, pharmaceutical, mining, and construction.

Dielectric properties

- Relative complex permittivity,

$$\varepsilon = \varepsilon' - j\,\varepsilon''$$

ε' is the dielectric constant

ε'' is the dielectric loss factor

- Loss tangent, $tan\ \delta = \varepsilon'' / \varepsilon'$
- Dielectric properties are dependent on frequency, temperature, moisture content, and bulk density.

RF moisture meters

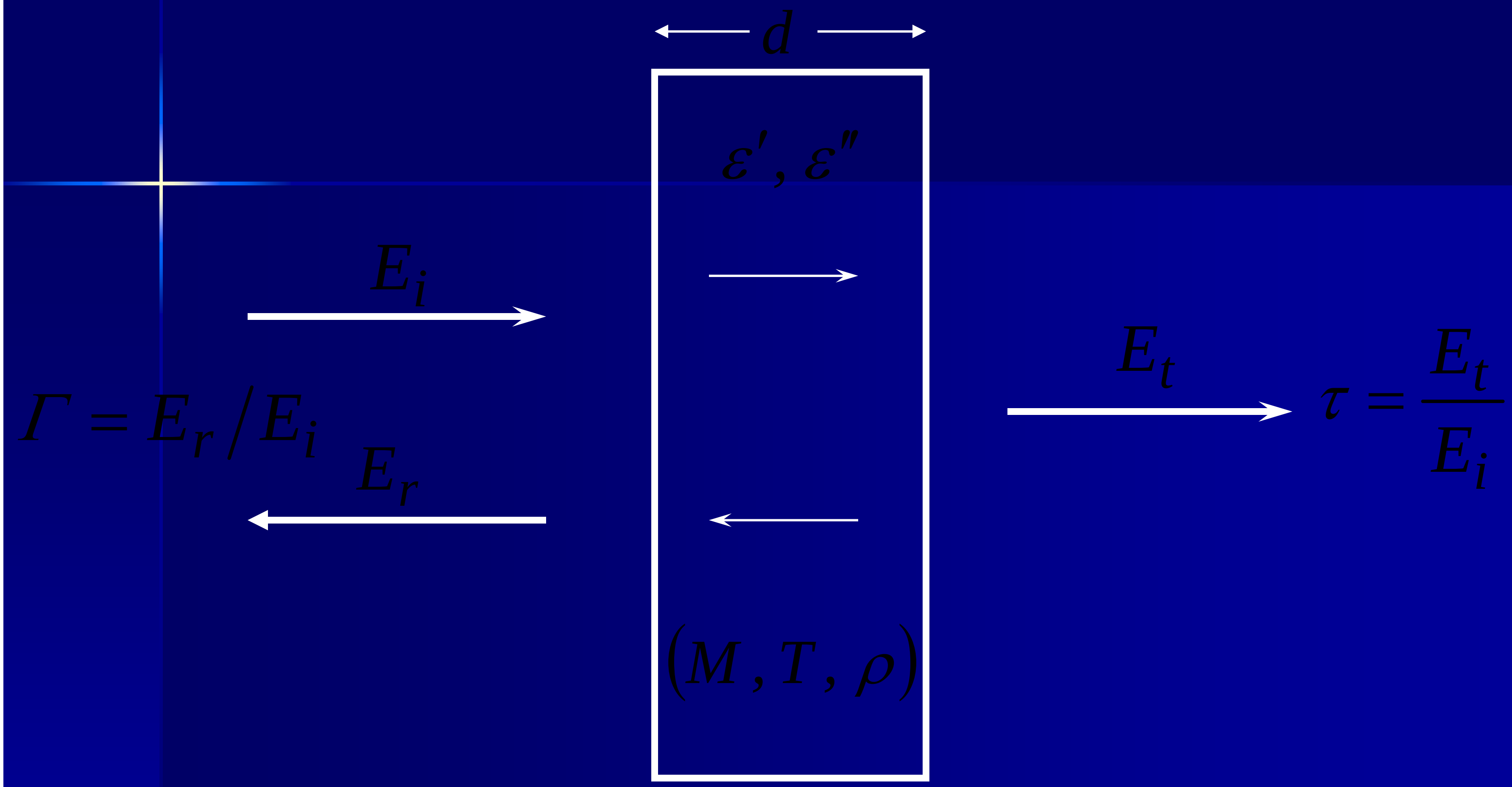
- Most operate at 1- to 20-MHz with parallel-plate or coaxial sample holders
- Influence of ionic conduction
- Readings must be corrected for temperature and bulk density variations
- Separate calibrations required for each kind of grain
- Bulk density fluctuations troublesome for on-line sensing in moving grain

Microwave moisture sensing

- Meters operate at a few GHz
- No ionic conduction influence
- Bulk density and moisture content can be determined simultaneously from same set of microwave measurements
- Moisture content can be determined independent of bulk density: density-independent calibration functions

Free-space transmission technique

- Nondestructive and no contact with sample necessary
- Minimal sample preparation required
- Measurement of attenuation and phase shift
- Information relative to entire interacting volume
- Principle can be easily implemented in on-line sensing applications, hand-held and laboratory devices.



d

$\varepsilon', \varepsilon''$

E_i

E_t

$\tau = \dfrac{E_t}{E_i}$

$\Gamma = E_r / E_i$

E_r

(M, T, ρ)

$$\Gamma = \frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}$$

$$\tau = e^{-j\frac{\omega}{c}\sqrt{\varepsilon\mu}\,d}$$

$$S_{21} = \frac{(1-\Gamma^2)\tau}{1-\Gamma^2\tau^2}$$

$$A = 20\,log\left|S_{21}\right|$$

$$\phi = Arg\left(S_{21}\right) - 2n\pi$$

$$\alpha = A/d,\ \beta = \phi / d + \beta_0,\ \beta_0 = 2\pi / \lambda_0$$

$$\varepsilon' = \left(\frac{\beta}{\beta_0}\right)^2 \qquad \varepsilon'' = \frac{2\alpha\beta}{{\beta_0}^2}$$

$$\varepsilon' = \left[1 - \frac{(\varphi - 360n)}{360d}\frac{c}{f}\right]^2$$

$$\varepsilon'' = \frac{-20\log\left|S_{21}\right|}{8.686\pi d}\frac{c}{f}\sqrt{\varepsilon'}$$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Shelled peanut samples

- Runner type peanuts, cv. Georgia green
- Bulk density: 0.63 g/cm^3 – 0.69 g/cm^3
- Moisture content: 4.9% – 25.6% w.b.
- Temperature: 1 ^{o}C – 38 ^{o}C
- Microwave measurements at 10 GHz

Density-independent functions

- Jacobsen et al., 1980

$$\psi_1 = \frac{A}{\phi}$$

- Meyer and Schilz, 1981

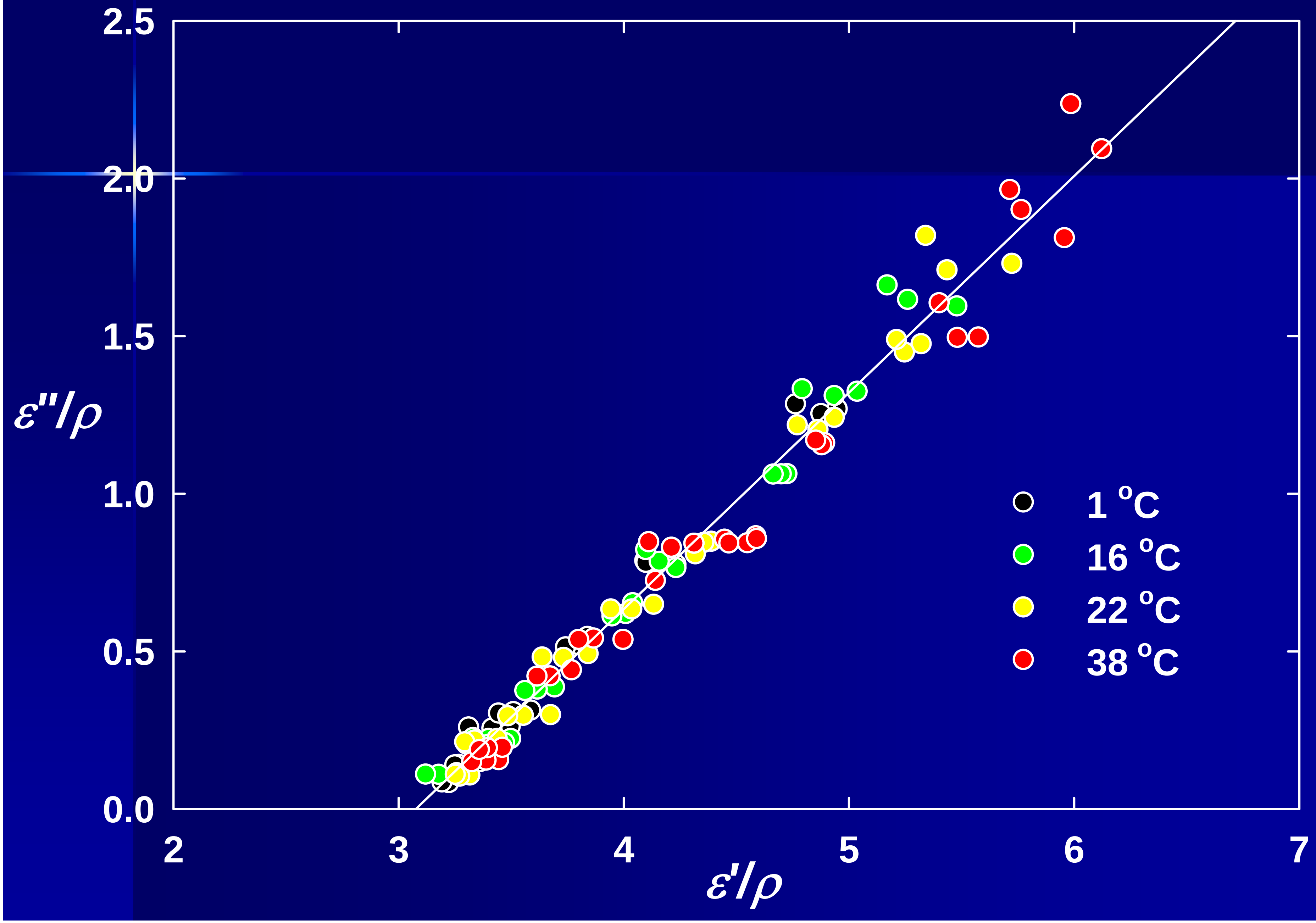
$$\psi_2 = \frac{\varepsilon''}{\varepsilon' - 1}$$

Density-independent functions (cont'd)

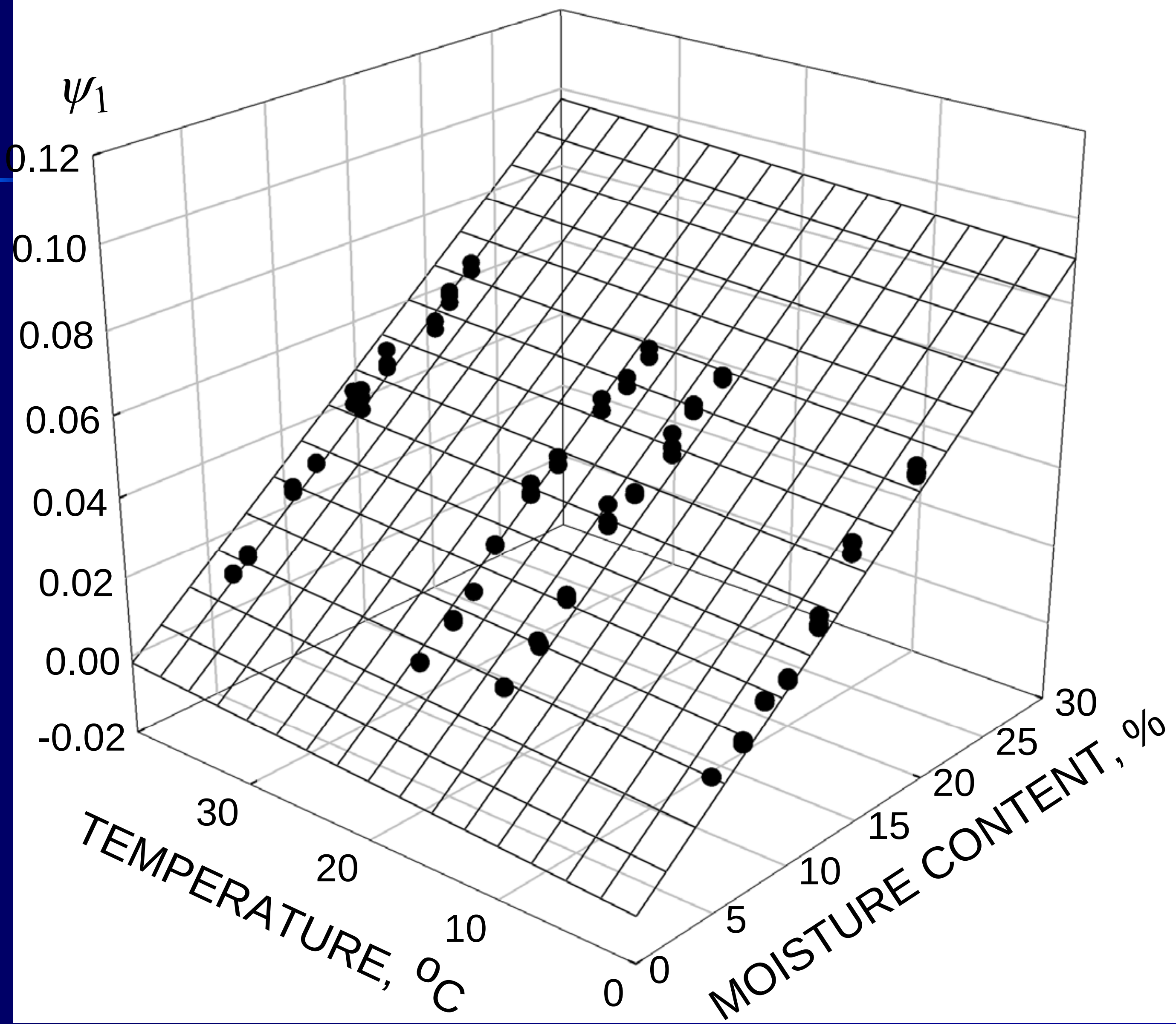
- Trabelsi et al. 1997

$$\psi_3 = \sqrt{\frac{\varepsilon''}{\varepsilon'\left(a_f\varepsilon' - \varepsilon''\right)}}$$

Where a_f is le slope in the complex plane representation ε''/ρ vs. ε'/ρ

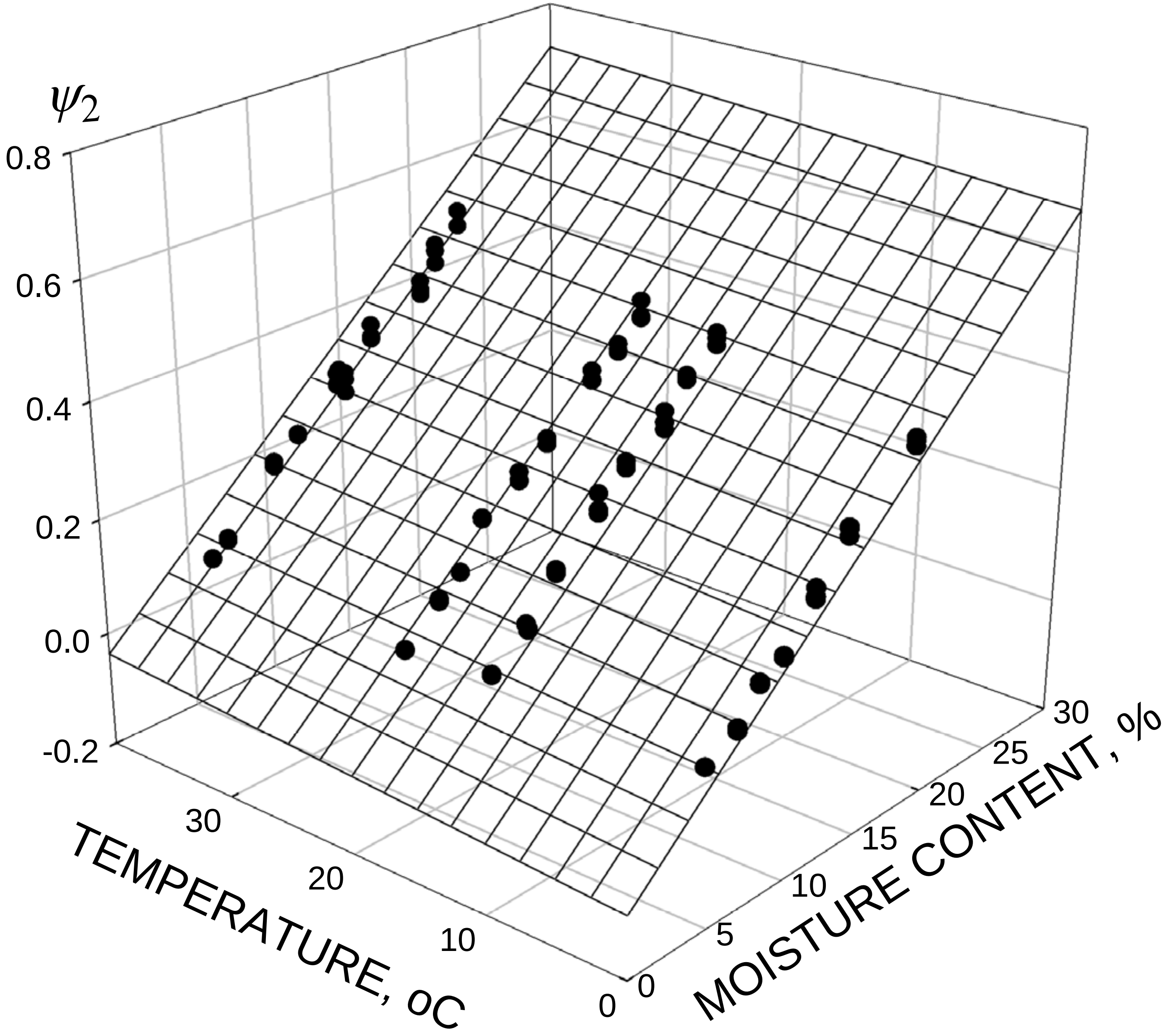

2.5
2.0
1.5
1.0
0.5
0.0
ε''/ρ
2
3
4
5
6
7
ε'/ρ
1 °C
16 °C
22 °C
38 °C

F=10 GHz



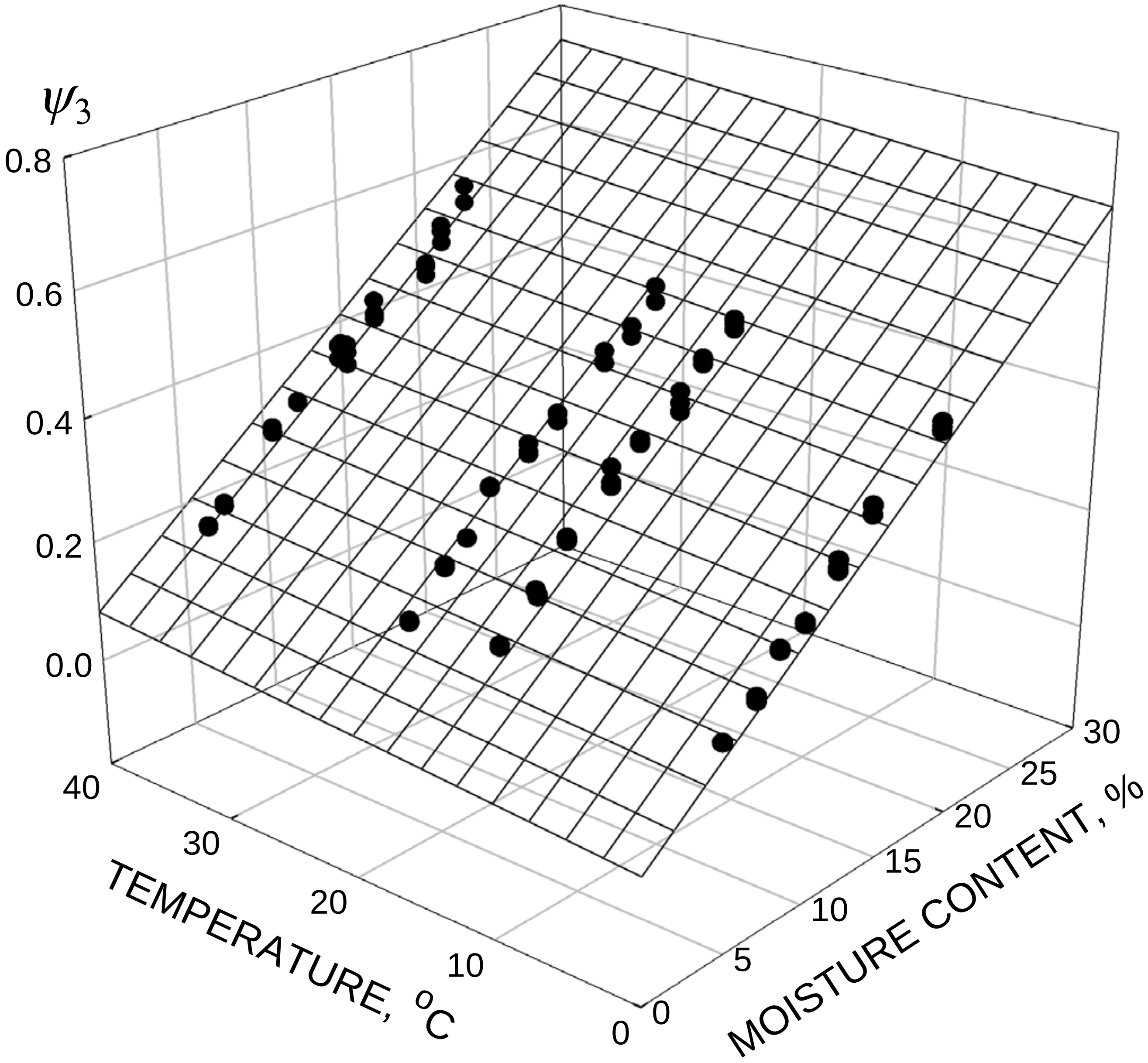
ψ_1
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
30
20
10
0
TEMPERATURE, ^oC
0
5
10
15
20
25
30
MOISTURE CONTENT, %

F=10 GHz



ψ_2
0.8
0.6
0.4
0.2
0.0
-0.2
30
20
10
0
TEMPERATURE, oC
0
5
10
15
20
25
30
MOISTURE CONTENT, %

F=10 GHz



ψ_3
0.8
0.6
0.4
0.2
0.0
40
30
20
10
0
TEMPERATURE, ^oC
0
5
10
15
20
25
30
MOISTURE CONTENT, %

Moisture content determination

- Correlation between ψ_i, M, and T:

$$\psi_i = a_i M + b_i T + c_i \qquad i = 1..3$$

- Moisture calibration equation:

$$M = \frac{\psi_i - b_i T - c_i}{a_i} \qquad i = 1..3$$

Results

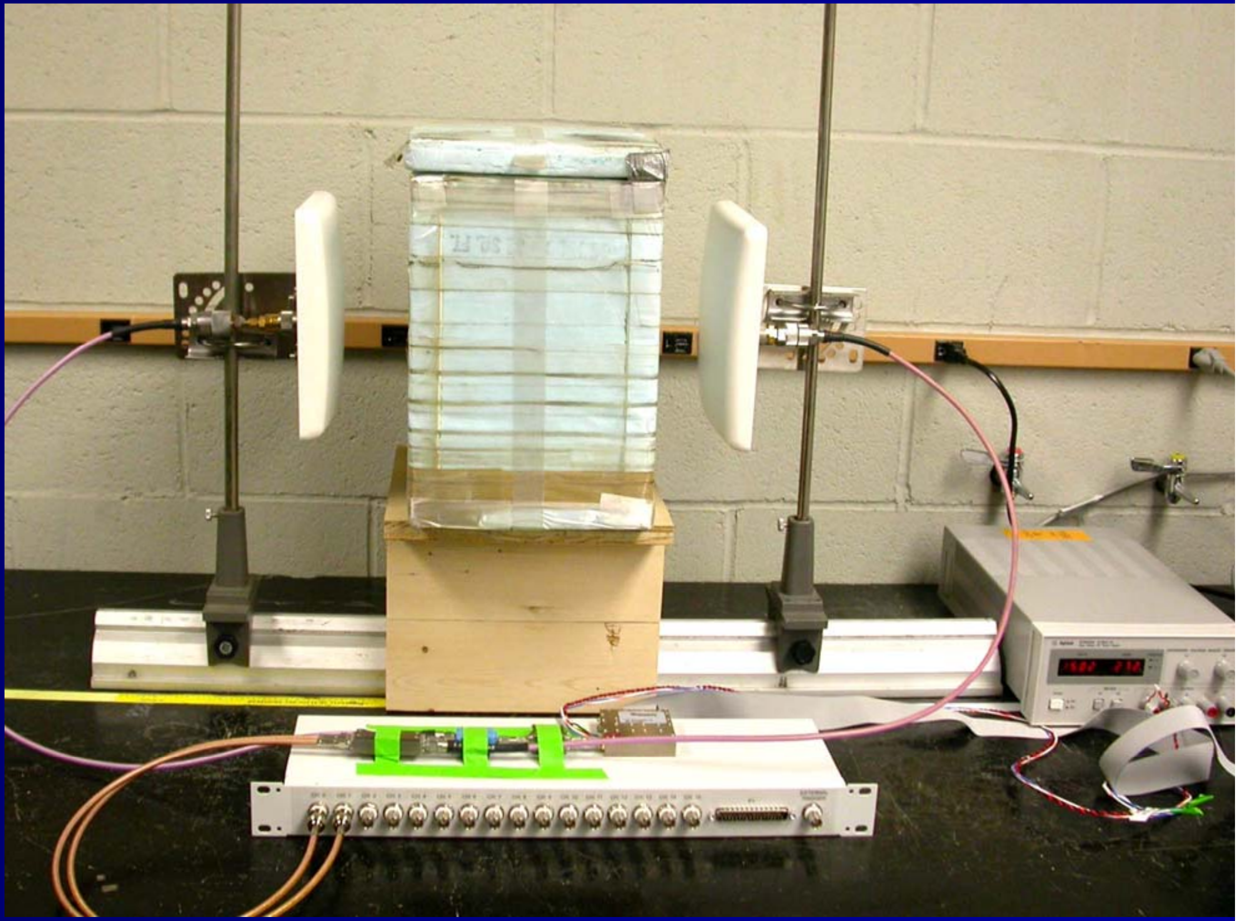
Calibration Function	a_i	b_i	c_i	r^2	SEC, %
ψ_1	0.0033	0.0002	-0.0086	0.97	0.8
ψ_2	0.0253	0.0013	-0.0911	0.98	0.6
ψ_3	0.0220	0.0014	0.0268	0.98	0.7

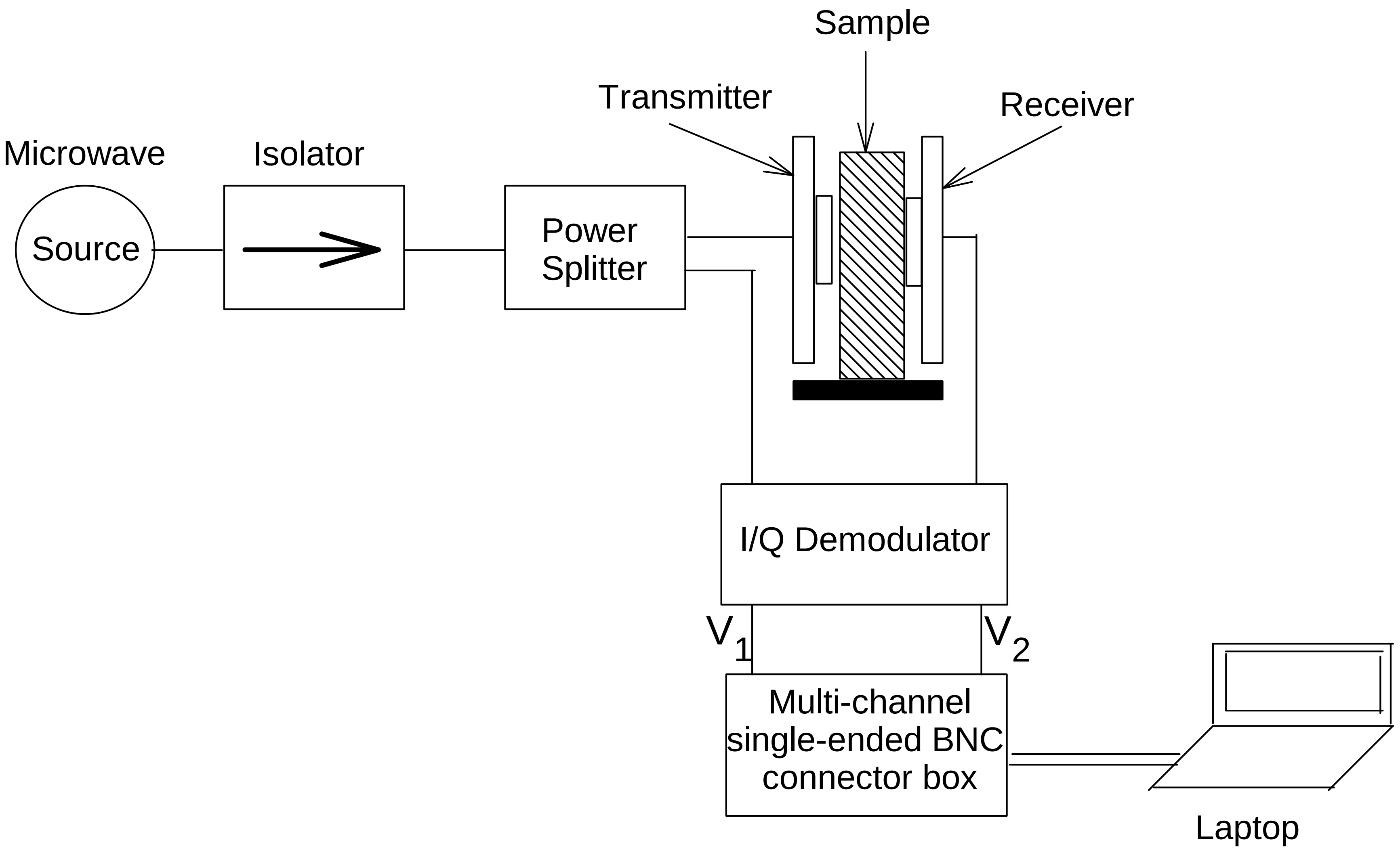
Conclusions

- Three density-independent functions were used to determine moisture content in shelled peanuts
- Moisture calibration equations with temperature compensation were provided
- SEC less than 1% moisture content with better results for ψ_2 and ψ_3

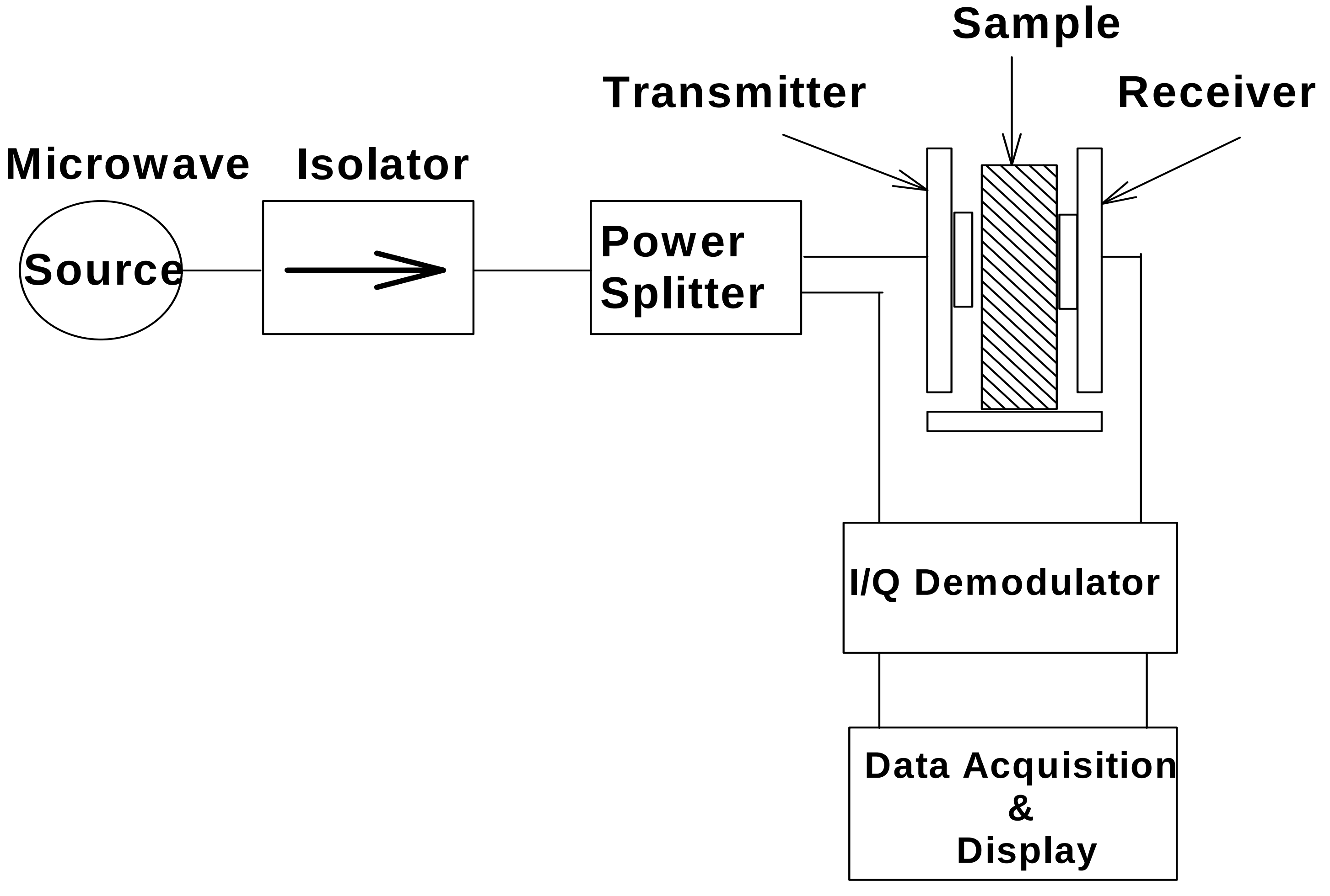
LABORATORY

SENSOR PROTOTYPE




Sample
Transmitter
Receiver
Microwave
Isolator
Source
Power Splitter
I/Q Demodulator
V_1
V_2
Multi-channel single-ended BNC connector box
Laptop

Sensor prototype



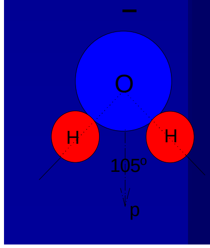
At a given frequency: $ka_f = constant$

$$\psi^2 = \frac{\varepsilon''}{\varepsilon'\left(a_f\varepsilon' - \varepsilon''\right)}$$

$$\psi = \sqrt{\frac{\varepsilon''}{\varepsilon'\left(a_f\varepsilon' - \varepsilon''\right)}}$$

Free-Space Transmission Technique

- Measurement of attenuation and phase shift
- Minimal sample preparation required
- No contact with sample necessary
- Principle can be easily implemented for on-line sensing



Relative complex permittivity

$$\varepsilon = \varepsilon' - j\varepsilon''$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

ε' is the dielectric constant

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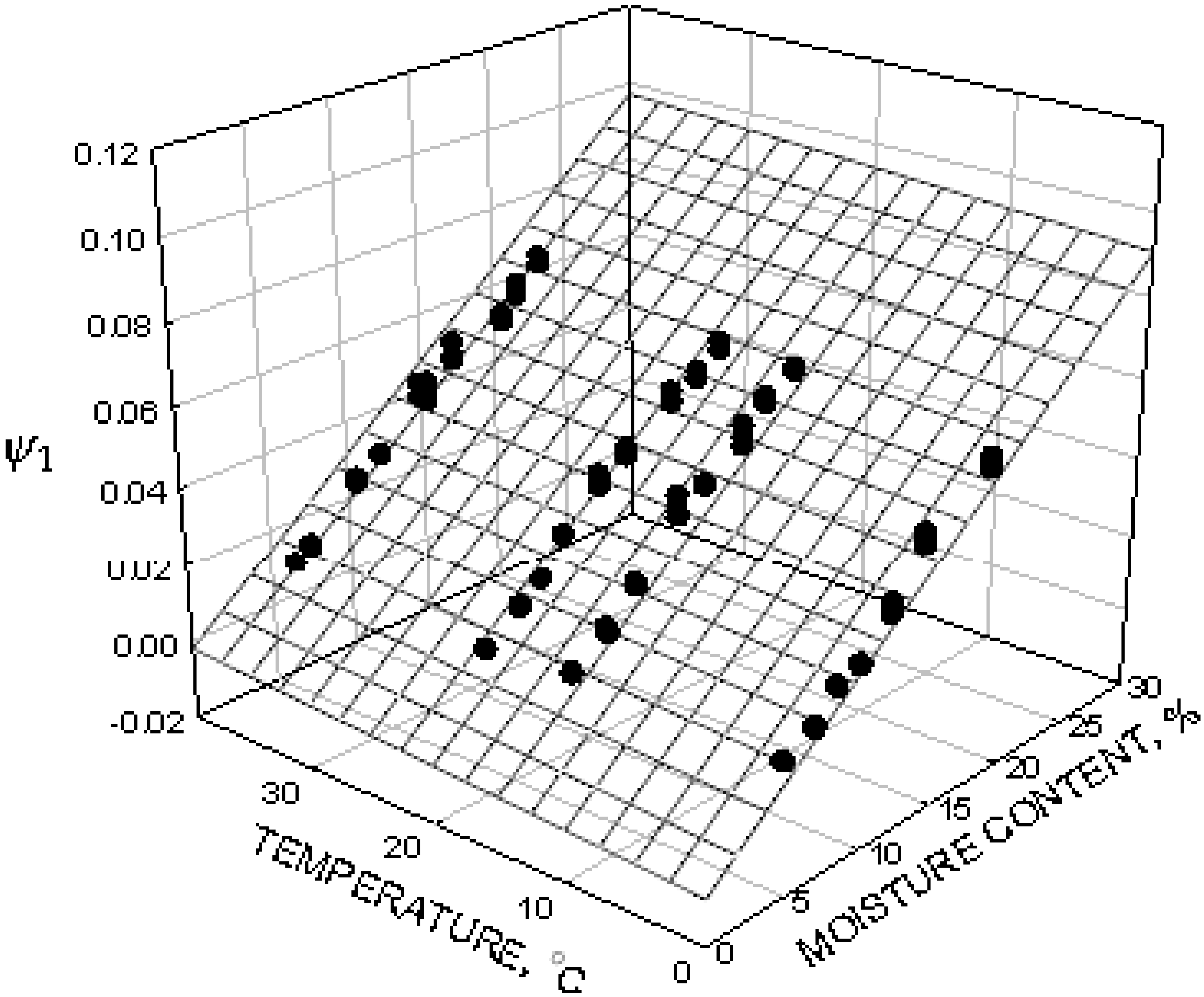
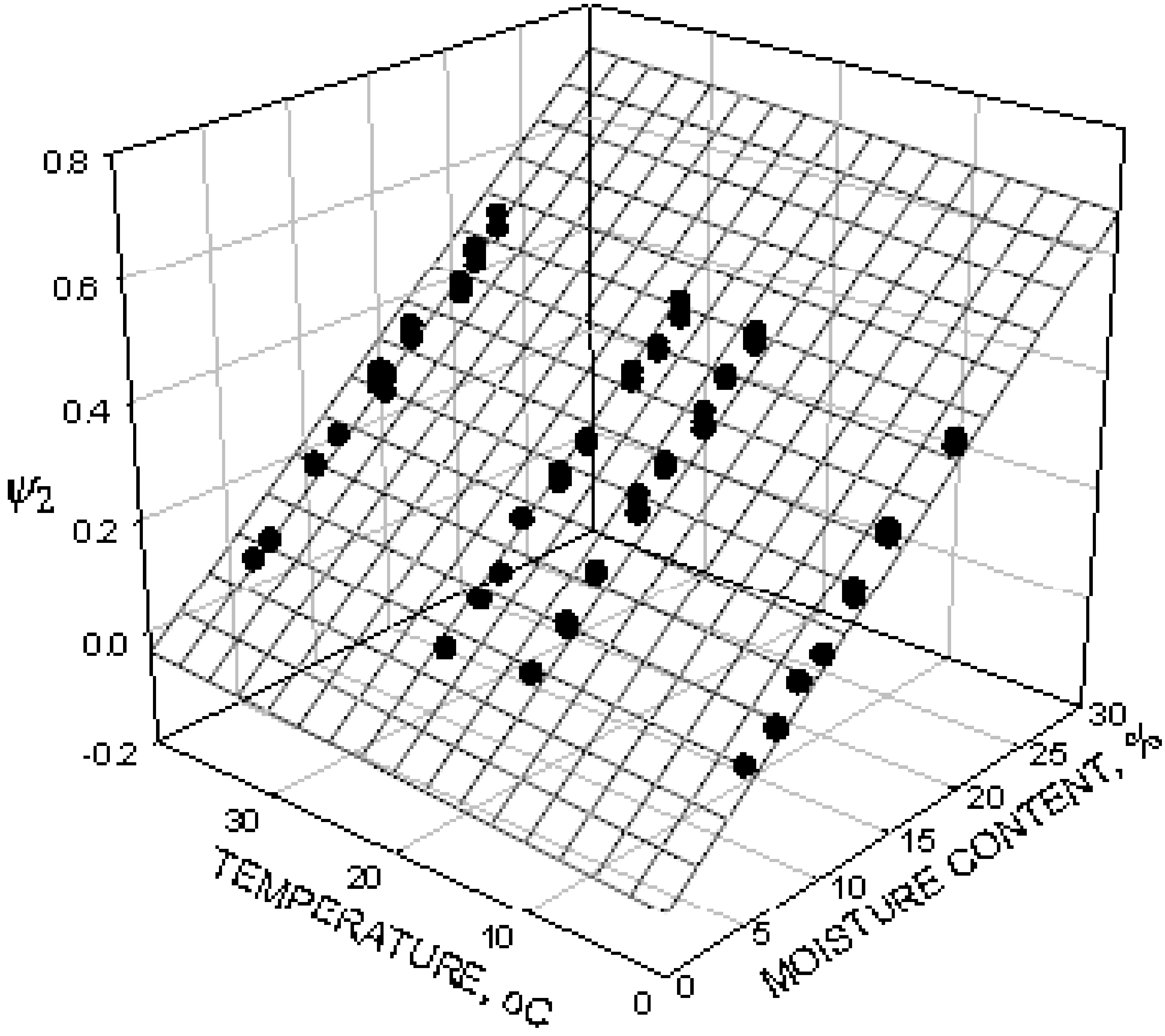
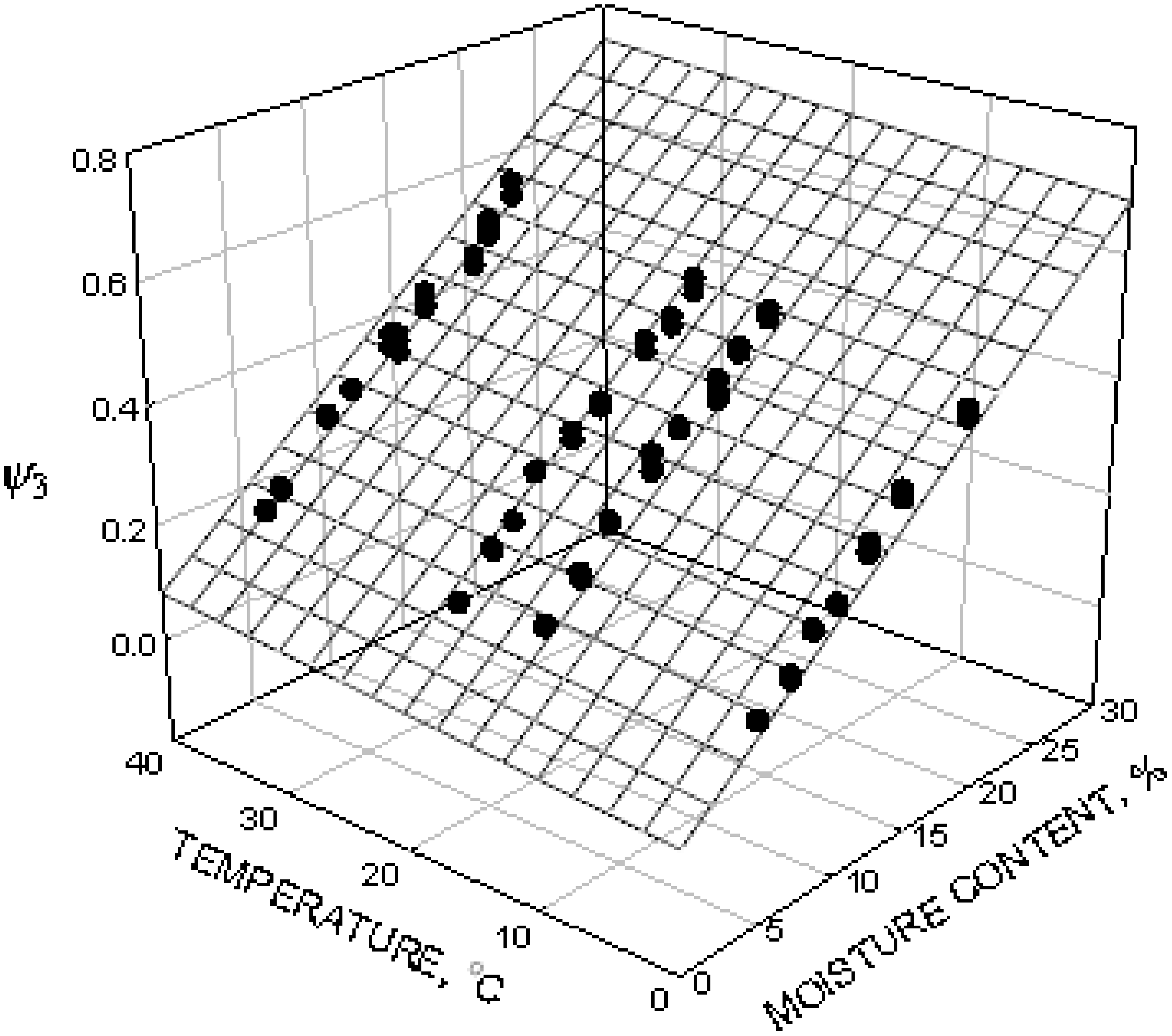

0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
ψ_1
30
20
10
0
TEMPERATURE, °C
0
5
10
15
20
25
30
MOISTURE CONTENT, %



ψ2
0.8
0.6
0.4
0.2
0.0
-0.2
30
20
10
0
TEMPERATURE, 0C
0
5
10
15
20
25
30
MOISTURE CONTENT, %


0.8
0.6
0.4
0.2
0.0
ψ_3
40
30
20
10
0
TEMPERATURE, °C
0
5
10
15
20
25
30
MOISTURE CONTENT, %