Biodegradable Hydrogel for Controlled Delivery of Biocontrol Bacteria and Micronutrients against *Macrophomina phaseolina*

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- **Fig. S3 (A & B):** Gel fraction composition of the synthesized hydrogel. The formulation included carrageenan (0.75% w/v), citric acid (0.75% w/v), sodium carboxymethyl cellulose (1% w/v), iron (0.005% w/v), zinc (0.005% w/v), and bacteria (3×10^9 CFU).
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SUPPLEMENATRY FIGURES

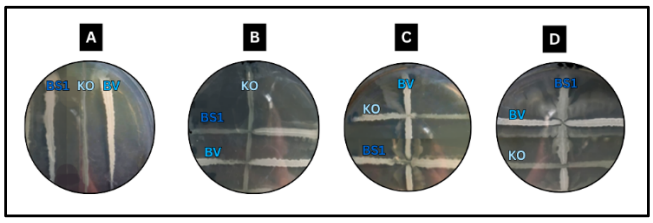

Fig. S1 (A-D): Biocompatibility assessment of bacterial strains *Bacillus velezensis* (BV), *Bacillus* sp. (BS1), and *Klebsiella oxytoca* (KO) on nutrient agar medium incubated at 30 °C.

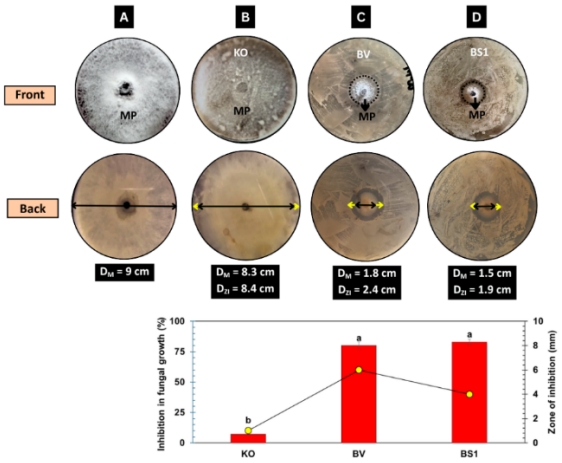

Fig. S2 (A-D): Antifungal activity of bacterial isolates against *Macrophomina phaseolina*. Control plate showing uninhibited mycelial growth (A). Mycelial growth inhibition by *Klebsiella oxytoca*, KA (B), *Bacillus velezensis*, BV (C), and *Bacillus* sp., BS1 (D) after 7 days of incubation at 30 °C.

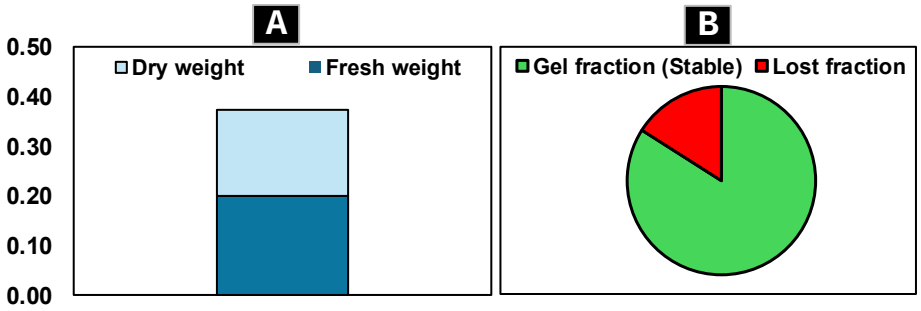

Fig. S3 (A & B): Gel fraction composition of the synthesized hydrogel. The formulation included carrageenan (0.75% w/v), citric acid (0.75% w/v), sodium carboxymethyl cellulose (1% w/v), iron (0.005% w/v), zinc (0.005% w/v), and bacteria (3×10^9 CFU).

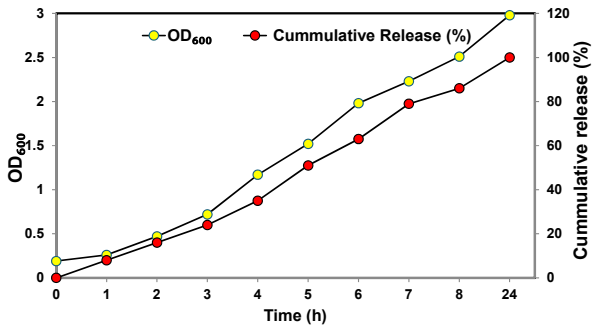

Fig. S4: Cumulative bacterial release over 24 h in phosphate-buffered saline (pH 7.0). The formulation included carrageenan (0.75% w/v), citric acid (0.75% w/v), sodium carboxymethyl cellulose (1% w/v), iron (0.005% w/v), zinc (0.005% w/v), and bacteria (3×10^9 CFU).

Table S1: Dissolution time (Dis_{time}) of different hydrogels.

	Car (g/L)	NaCMC (g/L)	Citric acid (g/L)	Zn (mg/L)	Fe (mg/L)	BV (CFU)	BS1 (CFU)	KO (CFU)	Stability (h)
HG_1	0.5	0.5	0.5	-	-	-	-	10^9	**3**
HG_2	0.5	0.75	0.5	5	-	10^9	10^9		**7**
HG_3	0.75	0.5	0.5	-	5	10^9	10^9	-	**5**
HG_4	1	0.75	0.5	-	5	10^9	-	10^9	**12**
HG_5	0.75	1	0.5	5	-	10^9	-	10^9	**14**
HG_6	1	0.75	0.75	5	5	10^9	10^9	10^9	**24**

Car-Carrageenan, NaCMC-Sodium Carboxymethyl cellulose, Zn-Zinc, Fe-Iron. BV- *Bacillus valezensis*, BS1- *Bacillus* sp., KO- *Klebsiella oxytoca*.

Table S2: Higuchi Model and Korsmeyer-Peppas models for hydrogel swelling behavior.

Model	Calculated Parameters	R^2	Interpretation
Higuchi Model $\mathbf{Qt = 0.137.t + 0.167}$	kH=0.14 g/min	**0.8**	Moderate correlation; diffusion plays a significant role, but not exclusively.
Korsmeyer-Peppas Model $\mathbf{\log\left(\frac{Qt}{Qe}\right) = 0.322.\log(t) - 0.655}$	kP=0.22, n=0.322	**0.92**	Better fit; *n<0.5,* indicating **Fickian diffusion** as the dominant mechanism.

Table 3S: Swelling ratios and Fickian diffusion suitability of hydrogel under varying electrolyte concentrations.

Electrolyte	Conc. (M)	Swelling (Q)	Diffusion
NaCl	0.1	4.25	Moderate
	0.3	**5.15**	**Optimal**
	0.5	3.70	Moderate
	0.7–0.9	3.40–3.05	Low
$CaCl_2$	0.1	4.35	Moderate
	0.3	4.30	Optimal
	0.5	**4.90**	Moderate
	0.7–0.9	3.85–3.75	Low

Table 4S: Germination parameters of maize seeds under control and hydrogel-treated conditions.

Parameter	Control	Hydrogel Treated
Germination percentage (%)	95	100
Mean Germination Time (MGT)	3.006 days	2.431 days
Germination Velocity (1/MGT)	0.333	0.411
Germination Index (GI)	9.35	12.44
Hydrogel Efficiency Ratio	-	1.11
Germination Rate	1.11 seeds/ day	1.67 seeds/ day

Table S4: Van Genuchten model parameters for hydrogels based on their porosity.

Van Genuchten model parameters for moisture retention $\theta(h) = \theta r + -\frac{\theta s - \theta r}{[1 + \lvert\theta h\rvert]^{n}]^{m}}$		
α, n, and m are empirical parameters	**Without hydrogel**	**With Hydrogel**
Residual Water Content (θr)	**0.10**	**0.10**
Saturated Water Content (θs)	**0.45**	**0.46**
Parameter α (cm⁻¹)	**0.015**	**0.018**
Parameter (n)	**1.50**	**1.60**
Parameter (m)	**0.33**	**0.38**