

A Bluetooth-Enabled Electrochemical Platform Based on *Saccharomyces cerevisiae* Yeast Cells for Copper Detection

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Supplementary Materials

Table S1: Current densities at 2500 s for biosensors prepared using WT *S. cerevisiae* cells cultured in YPD characterised using EmStat Pico in vertical assembly.

[Cu ²⁺] / μ M	Current Densities (WT (YPD) (Em-Stat))	SD
0	0.90874	0.02342
10	0.82172	0.01259
50	0.58664	0.02272
100	0.37728	0.01594

Table S2: Linear fitting and LoD calculations for current densities obtained at 2500 s for biosensors prepared using WT cells cultured in YPD and characterised using EmStat Pico in vertical assembly.

Fitting results			
Equation	$y = a + b \cdot x$		
Weight	Instrumental		
Residual Sum of Squares	4.7867		
Pearson's r	-0.996		
Adj. R-Square	0.98802		
		Value	Standard Error
B	Intercept	0.8768	0.01827
B	Slope	-0.00509	3.23E-04
LoD	-10.76817289		

Table S3: Comparison of current densities at 2500 s for biosensors prepared using WT cells cultured in YPD and characterised using EmStat Pico, single channel and multichannel potentiostat in vertical assembly [7, 13].

[Cu2+] / μ M	Current Densities (WT (YPD) (EmStat))	SD	Current Densities (WT (YPD) (single channel))	SD	Current Densities (WT (YPD) (Multichannel))	SD	Fold increase in EmStat w.r.t Single channel	Fold decrease in EmStat w.r.t Multichannel
0	0.90874	0.02342	0.64964	0.01797	1.6229	0.0054	1.398836279	1.785879349
10	0.82172	0.01259			1.4115	0.0281		1.717738402
20			0.50649	0.09484				
50	0.58664	0.02272	0.25671	0.03231	1.0006	0.031	2.285224572	1.705645711
100	0.37728	0.01594	0.15186	0.00855	0.5235	0.0091	2.48439352	1.387563613

Table S4: Comparison of LoD for biosensors prepared using WT cells cultured in YPD and characterised using single channel and multichannel potentiostat with EmStat Pico [7, 13].

System	LoD	Comparison	Fold change in LOD	
Multichannel system	2.2	EmStat vs Multichannel	4.863636364	Decrease
EmStat	10.7			
Single channel system	12.5	EmStat vs single channel	1.168224299	Increase

Table S5: Current densities at 1000 s for biosensors prepared using WT cells cultured in YPD and characterised using EmStat Pico in horizontal assembly.

[Cu2+] / μ M	WT(YPD) Horizontal	SD
0	9.91906	0.08635
100	8.53799	0.23961
200	7.65254	0.08472
300	6.75335	0.15035

Table S6: Linear fitting and LoD calculations for current densities obtained at 1000 s for biosensors prepared using WT cells cultured in YPD and characterised using EmStat Pico in horizontal assembly.

Fitting results WT-YPD			
Equation	$y = a + b \cdot x$		
Weight	Instrumental		
Residual Sum of Squares	2.53171		
Pearson's r	-0.99749		
Adj. R-Square	0.99248		
		Value	Standard Error
B	Intercept	9.87971	0.09307

B	Slope	-0.01088	5.46E-04
LoD	-25.66268		

Table S7: Current Densities at 1000 s for biosensors prepared using WT cells cultured in SCD and characterised using EmStat Pico in horizontal assembly.

[Cu2+] / uM	WT (SCD-Ura)	SD
0	9.71425	0.09362
100	8.40751	0.15001
200	7.64279	0.23954
300	6.51814	0.16621

Table S8: Linear fitting and LoD calculations for current densities obtained at 1000 s for biosensors prepared using WT cells cultured in SCD and characterised using EmStat Pico in horizontal assembly.

Fitting results WT-SCD minus Ura			
Equation	$y = a + b \cdot x$		
Weight	Instrumental		
Residual Sum of Squares	2.20749		
Pearson's r	-0.99647		
Adj. R-Square	0.98941		
		Value	Standard Error
B	Intercept	9.6688	0.09148
B	Slope	-0.0107	6.35E-04
LoD	-25.74484		

Table S9: Comparison of current densities for biosensors prepared using WT cells cultured in YPD and characterised using EmStat Pico in horizontal and vertical assemblies.

[Cu2+] / uM	WT (YPD) Horizontal	SD	WT (YPD) Vertical	SD	Fold increase in WT (YPD) horizontal w.r.t WT (YPD) vertical
0	9.91906	0.08635	0.90874	0.02342	10.91517926
100	8.53799	0.23961	0.37728	0.01594	22.63038062
200	7.65254	0.08472			
300	6.75335	0.15035			

Table S10: Comparison of current densities for biosensors prepared using WT cells cultured in SCD and YPD and characterised using EmStat Pico in horizontal and vertical assemblies, respectively.

[Cu2+] / uM	WT (SCD-Ura) Horizontal	SD	WT (YPD) Vertical	SD	Fold increase in WT (SCD-Ura) Horizontal w.r.t WT (YPD) Vertical
0	9.71425	0.09362	0.90874	0.02342	10.68980126
100	8.40751	0.15001	0.37728	0.01594	22.28453668
200	7.64279	0.23954			
300	6.51814	0.16621			

Table S11: Current Densities at 1000 s for biosensors prepared using C1 cells cultured in SCD-Ura and characterised using EmStat Pico in horizontal assembly.

[Cu2+] / μ M	C1	SD
0	7.17079	0.12043
100	6.58156	0.14251
200	5.86118	0.05938
300	4.96542	0.14797

Table S12: Linear fitting and LoD calculations for current densities obtained at 1000 s for biosensors prepared using C1 cells cultured in SCD-Ura and characterised using EmStat Pico in horizontal assembly.

Fitting Results C1			
Equation	$y = a + b \cdot x$		
Weight	Instrumental		
Residual Sum of Squares	1.8734		
Pearson's r	-0.9943		
Adj. R-Square	0.9829		
		Value	Standard Error
B	Intercept	7.23963	0.1012
B	Slope	-0.0071	5.36E-04
LoD	-43.003		

Table S13: Current Densities at 1000 s for biosensors prepared using C2 cells cultured in SCD-Ura and characterised using EmStat Pico in horizontal assembly.

[Cu2+] / μ M	C2	SD
0	13.61237	0.12369
100	11.40173	0.3005
200	10.29016	0.25946
300	8.68896	0.29214

Table S14: Linear fitting and LoD calculations for current densities obtained at 1000 s for biosensors prepared using C2 cells cultured in SCD-Ura and characterised using EmStat Pico in horizontal assembly.

Fitting results C2			
Equation	$y = a + b \cdot x$		
Weight	Instrumental		
Residual Sum of Squares	3.1049		
Pearson's r	-0.99534		
Adj. R-Square	0.98606		
		Value	Standard Error
B	Intercept	13.56017	0.14867
B	Slope	-0.01661	0.00114
LoD	-26.8519		

Table S15: Comparison of current densities for biosensors prepared using C1, C2 and WT cells characterised using EmStat Pico in horizontal assemblies.

[Cu ²⁺] / μ M	C1	SD	C2	SD	WT (SCD)	SD	Fold increase in C2 w.r.t C1	Fold increase in C2 w.r.t WT (SCD)	Fold decrease in C1 w.r.t WT (SCD)
0	7.17079	0.12043	13.6124	0.12369	9.71425	0.09362	1.898308276	1.401278534	0.738172273
100	6.58156	0.14251	11.4017	0.3005	8.40751	0.15001	1.732374999	1.356136359	0.78281917
200	5.86118	0.05938	10.2902	0.25946	7.64279	0.23954	1.755646474	1.346387903	0.766890102
300	4.96542	0.14797	8.68896	0.29214	6.51814	0.16621	1.749894269	1.333042862	0.761784804

Table S16: Comparison Table: Enzyme/Nanomaterial-based sensors and commercially available copper detection methods (2020 – 2025)

No.	Method & Type	Detection Range	Response Time	Cost / Operational Complexity	Reference
1	Current studies	LOD $\geq$ 2.2 μ M	$\leq$ 1000s to 2500s	Moderate: requires living cells and Web-application	[7,13]
2	Two-component CusRS biosensor (<i>E. coli</i>)	LOD $\approx$ 0.01 μ M	Rapid; high fluorescence, instrument-free	Moderate; requires engineered bacteria and fluorescence readout	[38]
3	Yeast-based genetic biosensor	Switch-like: 0.5–10 μ M shown	$\sim$ 24 h incubation	Moderate; engineered yeast, colorimetric/olfactory outputs	[15]
4	Microfluidic enzyme-HRP chip	3.91 nM – 256 μ M (LOD: 0.87 nM)	Rapid (naked-eye/spectrophotometric)	Moderate; microfluidic cartridge with enzyme assay	[39]
5	Just-Add-Water DNAzyme sensor	Threshold $\sim$ 20 μ M	$\leq$ 15 min	Low; freeze-dried reagents, no equipment required	[40]
6	QDs ratiometric probe	LOD 0.36 nM	Instant (UV-assisted)	Moderate; requires UV lamp for visualization	[41]
7	N-doped carbon nanodot dip strip (CNDs)	Visual $\geq$ 20 μ M; LOD 2.28 μ M	Instant, naked-eye	Low; simple paper strip with optical readout	[42]
8	Commercial dipstick	$\sim$ 0–47.2 μ M	Immediate, color chart	Very low; consumer-grade disposable strip	[43]
9	Commercial FSTest strips	$\sim$ 1.57–31.48 μ M	$\leq$ 30 seconds	Very low; low-cost, portable strips	[44]
10	Hach EZ1010 Copper Cu(II) Analyzer	$\sim$ 0.47–47.23 μ M (can extend via dilution)	10 min cycle time	High complexity; automated online analyzer with low μ g/L LOD	[45]
11	Sigma-Aldrich MQuant® Copper Test Strips	Semi-quantitative: $\sim$ 157–4722 μ M	Immediate (dip & read)	Very low cost; simple colorimetric strips for rough screening	[46]

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