Supplement of J. Sens. Sens. Syst., 15, 177–188, 2026
https://doi.org/10.5194/jsss-15-177-2026-supplement
© Author(s) 2026. CC BY 4.0 License.



JSSS Journal of Sensors and Sensor Systems Open Access

Supplement of

Multiplex measurement system for the detection of nutrients in hydroponics using ion-selective electrodes

Thomas Klotzbü et al.

Correspondence to: Thomas Klotzbücher (thomas.klotzbuecher@imm.fraunhofer.de)

The copyright of individual parts of the supplement might differ from the article licence.

Supplementary material

Table S1: Stock solution for the synthetic standard nutrient mixture (1000mg/L of targeted ions in DI water).

Sr. no.	Compound	Concentration	Target ion
1	Sodium phosphate dibasic (Na_2HPO_4)	12.50 g/L	HPO_4^{2-} (1000mg/L)
2	Sodium nitrate ($NaNO_3$)	60.66 g/L	NO_3^--N (1000mg/L)
3	Ammonium chloride (NH_4Cl)	38.18 g/L	NH_4^+-N (1000mg/L)
4	Calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$)	36.68 g/L	Ca^{2+} (1000mg/L)
5	Potassium chloride (KCl)	19.07 g/L	K^+ (1000mg/L)

Table S2: Synthetic standard nutrient mixture (test samples) for interference testing.

Sample ID	Target HPO_4^{2-} (mg/L)	Target Ca^{2+} (mg/L)	Target K^+ (mg/L)	Target NH_4^+-N (mg/L)	Target NO_3^--N (mg/L)
Mix-01	16.50	300.00	400.00	2.00	290.00
Mix-02	330.00	15.00	20.00	30.00	140.00
Mix-03	50.00	280.00	180.00	10.00	250.00
Mix-04	180.00	40.00	310.00	25.00	160.00
Mix-05	90.00	210.00	60.00	8.00	220.00
Mix-06	250.00	100.00	220.00	12.00	190.00

Table S3: Low and high calibration standard solutions for synthetic standard nutrient mixture samples testing.

Ion	Low [mg/L]	High [mg/L]
HPO_4^{2-}	16.50	330.00
NO_3^-	88.00	1771.00
Ca^{2+}	15.00	300.00
NH_4^+	25.00	514.00
K^+	20.00	400.00

Table S4: Chemical composition of the complex commercial nutrient mixture

Nutrient Element	Calculated value (Low calibration solution-0.5mS/cm)	Calculated value (High calibration solution 2.5mS/cm)
	mg/L	mg/L
N (NO_3)	44.49	222.49
N(NH_4^+)	4.23	21.17
HPO_4^{2-}	18.85	94.25
K^+	78.90	394.50
Ca^{2+}	36.45	182.25

Formulas:

1. **Relative Standard Deviation**

%RSD = (Standard deviation/Mean) *100

Where:

Standard Deviation): The scatter or spread of your individual data points around the average.
Mean: The average value of all your repeated measurements.

2. **Percent Recovery (%)**

% R = ($X_{measured}$ / $X_{expected}$) *100

Where:

$X_{Measured}$: It is the measured value of ions obtained through ICP-MS, colorimetric kits, or AutoNutri methods.
$X_{Expected}$: It is the expected value of ions obtained through calculations.

3. **Relative error (%)**

%RE = ($X_{measured} - X_{expected}$)/$X_{expected}$ * 100

Where:

$X_{Measured}$: It is the measured value of ions obtained through ICP-MS, colorimetric kits, or AutoNutri methods.
$X_{Expected}$: It is the expected value of ions obtained through calculations.

A. Testing & Validation for Standard Nutrient Mixture

Table S5: Comparison of the ICP-MS and colorimetric kit-based measured values with the expected concentration values for each standard ion in the synthetic standard nutrient mixture (mean± standard deviation).

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-01_R1	MIX-01_R2	MIX-01_R3	Average (mg/L)	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
Colorimetric method	NH_4^+-N	2.00	5.00	5.00	7.00	5.67	1.15	20.38	283.33	183.33
	NO_3^--N	290.00	250.00	300.00	350.00	300.00	50.00	16.67	103.45	3.45
ICP-MS method	HPO_4^{2-}	16.50	18.09	18.40	17.66	18.05	0.37	2.05	109.38	9.38
	K^+	400.00	445.00	464.00	457.00	455.33	9.61	2.11	113.83	13.83
	Ca^{2+}	300.00	312.00	321.00	315.00	316.00	4.58	1.45	105.33	5.33

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-02_R1	MIX-02_R2	MIX-02_R3	Average (mg/L)	Std deviation	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
Colorimetric method	NH_4^+-N	30.00	25.00	40.00	30.00	31.67	7.64	24.12	105.56	5.56
	NO_3^--N	140.00	150.00	150.00	170.00	156.67	11.55	7.37	111.90	11.90
ICP-MS method	HPO_4^{2-}	330.00	364.85	358.72	370.99	364.85	6.13	1.68	110.56	10.56
	K^+	20.00	21.30	21.30	21.50	21.37	0.12	0.54	106.83	6.83
	Ca^{2+}	15.00	16.00	15.80	17.40	16.40	0.87	5.32	109.33	9.33

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-03_R1	MIX-03_R2	MIX-03_R3	Average (mg/L)	Std deviation	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
Colorimetric method	NH_4^+-N	10.00	10.00	13.00	20.00	14.33	5.13	35.80	143.33	43.33
	NO_3^--N	250.00	250.00	250.00	300.00	266.67	28.87	10.83	106.67	6.67
ICP-MS method	HPO_4^{2-}	50.00	53.04	53.04	52.43	52.84	0.35	0.67	105.67	5.67
	K^+	180.00	185.00	187.00	189.00	187.00	2.00	1.07	103.89	3.89
	Ca^{2+}	280.00	288.00	290.00	293.00	290.33	2.52	0.87	103.69	3.69

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-04_R1	MIX-04_R2	MIX-04_R3	Average (mg/L)	Std deviation	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
Colorimetric method	NH_4^+-N	25.00	25.00	25.00	30.00	26.67	2.89	10.83	106.67	6.67
	NO_3^--N	160.00	150.00	150.00	190.00	163.33	23.09	14.14	102.08	2.08
ICP-MS method	HPO_4^{2-}	180.00	189.48	186.11	181.20	185.59	4.16	2.24	103.11	3.11
	K^+	310.00	345.00	351.00	344.00	346.67	3.79	1.09	111.83	11.83
	Ca^{2+}	40.00	41.80	43.20	41.30	42.10	0.98	2.34	105.25	5.25

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-05_R1	MIX-05_R2	MIX-05_R3	Average (mg/L)	Std deviation	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
Colorimetric method	NH_4^+-N	8.00	10.00	10.00	13.00	11.00	1.73	15.75	137.50	37.50
	NO_3^--N	220.00	200.00	200.00	250.00	216.67	28.87	13.32	98.48	-1.52
ICP-MS method	HPO_4^{2-}	90.00	93.51	94.13	91.98	93.21	1.11	1.19	103.56	3.56
	K^+	60.00	62.20	62.40	62.90	62.50	0.36	0.58	104.17	4.17
	Ca^{2+}	210.00	210.00	217.00	220.00	215.67	5.13	2.38	102.70	2.70

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-06_R1	MIX-06_R2	MIX-06_R3	Average (mg/L)	Std deviation	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
Colorimetric method	NH_4^+-N	12.00	10.00	10.00	15.00	11.67	2.89	24.74	97.22	-2.78
	NO_3^--N	190.00	180.00	200.00	200.00	193.33	11.55	5.97	101.75	1.75
ICP-MS method	HPO_4^{2-}	250.00	281.15	278.70	296.48	285.44	9.64	3.38	114.18	14.18
	K^+	220.00	243.00	245.00	254.00	247.33	5.86	2.37	112.42	12.42
	Ca^{2+}	100.00	88.50	90.30	93.80	90.87	2.70	2.97	90.87	-9.13

Table S6: Comparison of the AutoNutri measured values with the expected concentration values for each standard ion in the synthetic standard nutrient mixture (mean± standard deviation).

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-01_R1	MIX-01_R2	MIX-01_R3	Average	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
AutoNutri method	NH_4^+-N	2.00	2.31	2.74	2.65	2.57	0.22	8.67	128.50	28.29
	NO_3^--N	290.00	278.33	291.72	289.63	286.56	7.21	2.52	98.81	-1.19
	HPO_4^{2-}	16.50	14.34	22.44	26.75	21.18	6.30	29.74	128.36	28.35
	K^+	400.00	384.96	397.06	425.81	402.61	20.98	5.21	100.65	0.65
	Ca^{2+}	300.00	314.01	286.77	308.57	303.12	14.41	4.75	101.04	1.04

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-02_R1	MIX-02_R2	MIX-02_R3	Average	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
AutoNutri method	NH_4^+-N	30.00	27.28	28.39	27.60	27.75	0.57	2.06	92.50	-7.48
	NO_3^--N	140.00	155.42	164.53	147.32	155.76	8.61	5.53	111.26	11.25
	HPO_4^{2-}	330.00	310.39	370.33	363.84	348.19	32.89	9.45	105.51	5.51
	K^+	20.00	29.39	31.17	31.72	30.76	1.22	3.95	153.80	53.79
	Ca^{2+}	15.00	24.06	29.82	23.66	25.85	3.45	13.35	172.33	72.31

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-03_R1	MIX-03_R2	MIX-03_R3	Average	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
AutoNutri method	NH_4^+-N	10.00	9.77	11.57	7.34	9.56	2.13	22.25	95.60	-4.40
	NO_3^--N	250.00	233.29	271.82	269.76	258.29	21.68	8.39	103.32	3.32
	HPO_4^{2-}	50.00	49.51	54.05	57.13	53.56	3.84	7.16	107.12	7.12
	K^+	180.00	136.74	166.84	189.84	164.47	26.63	16.19	91.37	-8.63
	Ca^{2+}	280.00	266.37	272.43	283.81	274.20	8.85	3.23	97.93	-2.07

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-04_R1	MIX-04_R2	MIX-04_R3	Average	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
AutoNutri method	NH_4^+-N	25.00	19.79	27.49	22.48	23.25	3.91	16.81	93.00	-6.99
	NO_3^--N	160.00	173.91	161.76	182.66	172.78	10.49	6.07	107.99	7.99
	HPO_4^{2-}	180.00	189.35	167.05	167.83	174.74	12.66	7.24	97.08	-2.92
	K^+	310.00	298.18	282.04	287.90	289.38	8.17	2.82	93.35	-6.65
	Ca^{2+}	40.00	40.39	43.99	58.71	47.70	9.70	20.34	119.25	19.24

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-05_R1	MIX-05_R2	MIX-05_R3	Average	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
AutoNutri method	NH_4^+-N	8.00	10.56	9.00	10.71	10.09	0.95	9.37	126.13	26.15
	NO_3^--N	220.00	226.45	220.42	200.42	215.76	13.62	6.31	98.07	-1.93
	HPO_4^{2-}	90.00	70.26	106.68	82.28	86.41	18.56	21.48	96.01	-3.99
	K^+	60.00	60.71	66.24	60.45	62.47	3.27	5.24	104.12	4.11
	Ca^{2+}	210.00	191.05	189.16	197.74	192.65	4.50	2.34	91.74	-8.26

Analysis method	Element Present	Expected Conc. of target element (mg/L)	MIX-06_R1	MIX-06_R2	MIX-06_R3	Average	Std deviation (SD)	Relative standard deviation (%)	Percent Recovery (%)	Relative error (%) (measured values Vs expected values)
AutoNutri method	NH_4^+-N	12.00	11.18	13.86	16.28	13.77	2.55	18.53	114.75	14.76
	NO_3^--N	190.00	206.61	194.90	197.52	199.68	6.15	3.08	105.09	5.09
	HPO_4^{2-}	250.00	241.17	234.00	237.62	237.60	3.59	1.51	95.04	-4.96
	K^+	220.00	229.56	208.78	232.18	223.51	12.82	5.74	101.60	1.59
	Ca^{2+}	100.00	115.79	105.68	95.46	105.64	10.16	9.62	105.46	5.64

B. Testing & Validation for Commercial Nutrient Mixture

Table S7: Comparison of the ICP-MS and colorimetric kit-based measured values with the expected concentration values for each standard ion in the complex commercial nutrient mixture.

Complex commercial nutrient mixture-A (EC 1.0 mS/cm)										
Analysis method	**Element Present**	**Expected Conc. of target element (mg/L)**	**MIX-A_R1 (mg/L)**	**MIX-A_R2 (mg/L)**	**MIX-A_R3 (mg/L)**	**Average (mg/L)**	**Std deviation (SD)**	**Relative standard deviation (%)**	**Percent Recovery (%)**	**Relative error (%)**
Colorimetric method	NH_4^+-N	8.47	25.00	13.00	10.00	16.00	7.94	49.61	188.90	88.90
	NO_3^--N	88.99	100.00	50.00	100.00	83.33	28.87	34.64	93.64	-6.36
ICP-MS method	HPO_4^{2-}	37.70	31.60	40.10	56.90	42.87	12.87	30.03	113.70	13.70
	K^+	157.80	128.00	162.00	229.00	173.00	51.39	29.71	109.63	9.63
	Ca^{2+}	72.90	69.30	88.20	125.00	94.17	28.33	30.08	129.17	29.17
Complex commercial nutrient mixture-B (EC 1.4 mS/cm)										
Analysis method	**Element Present**	**Expected Conc. of target element (mg/L)**	**MIX-B_R1 (mg/L)**	**MIX-B_R2 (mg/L)**	**MIX-B_R3 (mg/L)**	**Average (mg/L)**	**Std deviation (SD)**	**Relative standard deviation (%)**	**Percent Recovery (%)**	**Relative error (%)**
Colorimetric method	NH_4^+-N	11.85	30.00	10.00	10.00	16.67	11.55	69.28	140.65	40.65
	NO_3^--N	124.58	100.00	100.00	150.00	116.67	28.87	24.74	93.65	-6.35
ICP-MS method	HPO_4^{2-}	52.80	32.70	45.80	61.20	46.57	14.27	30.63	88.19	-11.81
	K^+	220.90	129.00	177.00	245.00	183.67	58.29	31.74	83.14	-16.86
	Ca^{2+}	102.00	69.80	101.00	135.00	101.93	32.61	31.99	99.93	-0.07
Complex commercial nutrient mixture-C (EC 1.8 mS/cm)										
Analysis method	**Element Present**	**Expected Conc. of target element (mg/L)**	**MIX-C_R1 (mg/L)**	**MIX-C_R2 (mg/L)**	**MIX-C_R3 (mg/L)**	**Average (mg/L)**	**Std deviation (SD)**	**Relative standard deviation (%)**	**Percent Recovery (%)**	**Relative error (%)**
Colorimetric method	NH_4^+-N	15.24	25.00	13.00	10.00	16.00	7.94	49.61	104.99	4.99
	NO_3^--N	160.18	150.00	150.00	160.00	153.33	5.77	3.77	95.73	-4.27
ICP-MS method	HPO_4^{2-}	67.90	40.50	53.60	60.80	51.63	10.29	19.93	76.04	-23.96
	K^+	284.00	160.00	220.00	245.00	208.33	43.68	20.97	73.36	-26.64
	Ca^{2+}	131.20	87.60	117.00	134.00	112.87	23.47	20.80	86.03	-13.97

Table S8: Comparison of the AutoNutri system-measured values with the expected concentration values for each standard ion in the complex commercial nutrient mixture.

Complex commercial nutrient mixture-A (EC 1.0 mS/cm)										
Analysis method	**Element Present**	**Expected Conc. of target element (mg/L)**	**MIX-A_R1 (mg/L)**	**MIX-A_R2 (mg/L)**	**MIX-A_R3 (mg/L)**	**Average (mg/L)**	**Std deviation (SD)**	**Relative standard deviation (%)**	**Percent Recovery (%)**	**Relative error (%)** (AutoNutri against expected values)
AutoNutri method	NH_4^+-N	8.47	8.77	9.13	10.31	9.40	0.81	8.57	111.02	11.02
	NO_3^--N	88.99	89.41	93.74	86.87	90.01	3.47	3.86	101.14	1.14
	HPO_4^{2-}	37.7	42.08	39.06	36.46	39.20	2.81	7.18	103.98	3.98
	K^+	157.8	179.45	177.17	174.02	176.88	2.73	1.54	112.09	12.09
	Ca^{2+}	72.9	83.75	76.68	74.88	78.44	4.69	5.98	107.59	7.59
Complex commercial nutrient mixture-B (EC 1.4 mS/cm)										
Analysis method	**Element Present**	**Expected Conc. of target element (mg/L)**	**MIX-B_R1 (mg/L)**	**MIX-B_R2 (mg/L)**	**MIX-B_R3 (mg/L)**	**Average (mg/L)**	**Std deviation (SD)**	**Relative standard deviation (%)**	**Percent Recovery (%)**	**Relative error (%)** (measured values Vs expected values)
AutoNutri method	NH_4^+-N	11.85	15.73	15.89	14.56	15.39	0.72	4.71	129.91	29.91
	NO_3^--N	124.58	143.36	121.77	139.89	135.01	11.59	8.59	108.37	8.37
	HPO_4^{2-}	52.8	68.74	53.56	58.54	60.28	7.74	12.84	114.16	14.16
	K^+	220.9	221.37	224.42	219.72	221.84	2.39	1.08	100.42	0.42
	Ca^{2+}	102	113.01	110.36	102.54	108.64	5.44	5.01	106.51	6.51
Complex commercial nutrient mixture-C (EC 1.8 mS/cm)										
Analysis method	**Element Present**	**Expected Conc. of target element (mg/L)**	**MIX-C_R1 (mg/L)**	**MIX-C_R2 (mg/L)**	**MIX-C_R3 (mg/L)**	**Average (mg/L)**	**Std deviation (SD)**	**Relative standard deviation (%)**	**Percent Recovery (%)**	**Relative error (%)** (measured values Vs expected values)
AutoNutri method	NH_4^+-N	15.24	14.84	17.49	16.75	16.36	1.37	8.38	107.35	7.35
	NO_3^--N	160.18	141.98	140.73	154.53	145.74	7.63	5.24	90.99	-9.01
	HPO_4^{2-}	67.9	81.04	74.32	77.84	77.73	3.36	4.32	114.48	14.48
	K^+	284	295.04	297.82	281.29	291.38	8.85	3.04	102.60	2.60
	Ca^{2+}	131.2	137.27	121.56	149.36	136.06	13.94	10.25	103.71	3.71

Table S9: Comparison of the AutoNutri measured values with reference method for each standard ion in the complex commercial nutrient mixture (Mean± Standard deviation).

Element Present	Total Expected Conc. of target element (mg/L)	ICP-MS measured value (mg/L)	Colorimetric kit-based method measured value (mg/L)	AutoNutri measured value (mg/L)	Recovery of Autonutri (%) against reference method	Absolute error (AutoNutri Vs reference method)	Relative error % (AutoNutri Vs reference method)
Complex commercial nutrient Mixture A (EC 1.0mS/cm)							
NH_4^+-N	8.47	N/A	16.00±7.94	9.40±0.81	58.75	-6.60	-41.25
NO_3^--N	88.99	N/A	83.33±28.87	90.01±3.47	108.02	6.67	8.00
HPO_4^{2-}	37.70	42.87±12.87	N/A	39.20±2.81	91.44	-3.67	-8.56
K^+	157.80	173.00±51.39	N/A	176.88±2.73	102.24	3.88	2.24
Ca^{2+}	72.90	94.17±28.33	N/A	78.44±4.69	83.30	-15.74	-16.71
Complex commercial nutrient Mixture B (EC 1.4mS/cm)							
NH_4^+-N	11.85	N/A	16.67±11.55	15.39±0.72	92.32	-1.28	-7.68
NO_3^--N	124.58	N/A	116.67±28.87	135.01±11.59	115.72	18.34	15.72
HPO_4^{2-}	52.80	46.57±14.27	N/A	60.28±7.74	129.42	13.70	29.42
K^+	220.90	183.67±58.29	N/A	221.84±2.39	120.78	38.16	20.78
Ca^{2+}	102.00	101.93±32.61	N/A	108.64±5.44	106.58	6.70	6.57
Complex commercial nutrient Mixture C (EC 1.8mS/cm)							
NH_4^+-N	15.24	N/A	16.00±7.94	16.36±1.37	102.25	0.36	2.25
NO_3^--N	160.18	N/A	153.33±5.77	145.74±7.63	95.05	-7.59	-4.95
HPO_4^{2-}	67.90	51.63±10.29	N/A	77.73±3.36	150.55	26.10	50.55
K^+	284.00	208.33±43.68	N/A	291.38±8.85	139.86	83.05	39.86
Ca^{2+}	131.20	112.87±23.47	N/A	136.06±13.94	120.55	23.19	20.55