Grant Code:	New
Title:	Development of In-plant Sap Sensor for Aluminum Toxicity in Wheat and Lime Treatment evaluation
Personnel:	Johnny Li, Assistant Professor in Precision Agriculture, Soil & Water Systems Daniel Strawn, Professor in Environmental Soil Chemistry Kurt Schroeder, Associate Professor & Cropping Systems Agronomist
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Justification/Rationale:

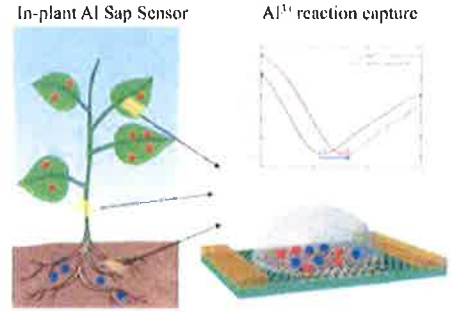

Fig.1 In-plant Al sap sensing for lime treatment

Globally, about 50% of all arable soils are classified as acidic. According to this meta-analysis from 1570 observations reported in 121 field-based studies worldwide (Wang 2021), liming of agricultural acid soils can significantly increases crop yield by 36.3%, which result in a global increase of upland crop yields by 7.70×10^8 Mg, rice yields by 0.56×10^8 Mg, and grass production by 5.90×10^8 Mg every year. Based on FAOstats data of the average food demand per capita over the world (FAO, 2013), the estimated liming-induced increment in crop and biomass production has the potential to feed nearly 1261 million people in the future. Development will empower long-term, high-resolution, cost-effective monitoring of soil health, plant-soil-microbial interactions across a range of soil properties and improve the crop development and productivity on soils impacted by soil acidity; approximately 50% of the world's arable land. Application of in-situ plant Al sap sensor for real-time soil acidity and Al toxicity in plant monitoring and plant improvement has not been reported in the available literature. Development of long-term, high-resolution, cost-effective monitoring of soil health, plant-soil-microbial interactions across a range of soil properties and improve the crop development and productivity on soils impacted by soil acidity; approximately 50% of the world's arable land. Currently, available Al for plant uptake is assessed by extraction of soil with KCl or $CaCl_2$ solutions (Sparks 1996, Yang 2022). However, the actual plant uptake may be quite different than the soil extract predicted bioavailability and depends on the crop cultivar genotype and soil physicochemical conditions. Standard soil test, plant leaf tissue analysis and plant sap test were destructive, labor- and time-intensive and requires periodic leaf samplings over growing season to determine its present nutrient available in plant (Hochmuth 2022, Morita 2004). It is hard for the current leaf sap test to achieve consistent measurement over weather event (dry or rain) or foliar application, which is impossible for in-season soil amendment and crop management. Therefore, it is critical to develop in-plant Al sap sensor to acquire new knowledge and preliminary data related to plant sap sampling, soluble Al agent chemical reaction, in-situ Al toxicity analysis, wireless communication strategy, and their integration for controlled lab condition test and field trials.

Objectives:

This project will address these specific needs in Northwest Palouse region by advancing in-plant Al sap sensor development and testing of wheat plant Al toxicity and lime treatment performance assessment in acid soils. Our three objectives are: (1) Develop and validate an in-plant Al sap sensor based on Hydrogel Ionic Gated MXene-Graphene FET under different Al chemical forms/concentration and pH levels in the laboratory; 2) calibrate in-plant sap sensor using extracted sap samples from wheat grown in various soluble Al concentrations in the greenhouse and compare results to standard soil and plant tests used to predict Al toxicity; and 3) validate the field deployment feasibility of in-plant Al sap sensor for in-field Al toxicity monitoring in an existing soil acidity and lime treatment research trial in Potlatch, ID and at the USDA LTAR Cook Agronomy Farm(CAF). The new in-plant sap sensor will allow for real-time field measurement of Al in plant sap, leading to in-season lime treatment and correction of Al toxicity in an efficient precision manner.

Methods/Plan of Work:

The long-term goal of this project is to increase agricultural crop productivity in acid soil and reduce the aluminum (Al) toxicity by optimizing the lime treatment impact in plants through a novel/transformative in-plant Al sap sensor to real-time monitor soil acidity and Al toxicity in plant continuously and efficiently. The sensor makes direct measurement of signal change (Dirac point shift) caused by the reactions between OH^-, soluble Al species (Al_m^+) in the sap and the corresponding hydrogel ionic gated agents Ti_3C_2 and $(Ti_3C_2O)^-$ in the sensor respectively (Fig.1). The in-plant Al sap sensor prototype will be evaluated in Palouse Research, Extension and Ed. Center Greenhouses coordinated by Co-PI Dr. Daniel Strawn at University of Idaho and field trials at the two liming sites at Potlatch and Moscow at ID led by Co-PI Dr. Kurt Schroeder as well as *the USDA* ARS Long-term Agricultural Research site in Pullman, Washington directed by Dr. Dave Huggins. Soils at these site have become acidified from years of ammoniacal fertilizer application. Tasks for **objective 1** including Characterization of Al chemical forms and its reaction. The concentrations of Al^{3+} species and the total soluble Al in soil, will suffice to predict toxicity (Sparling 1996). These species increase the solubility of total Al in solution, and their concentrations varied at different pH levels. We will characterize and quantify signal change (Dirac point shift) of total Al and its key forms in the plant sap and using controlled standard Al solutions with various hydrolysis species (pH 4.5-7.5) and chelated Al species made with citric acid and oxalic acid as representative model plant sap species. Solution speciation will be modeled using aqueous thermodynamic solubility, hydrolysis, and complexation constants in PHREEQC (Parkhurst 1995). The sensitivity of the corresponding signal change in the hydro-gel-ionic-gated MXene-Graphene FET based plant Al sap sensor and its chemical reaction agent will be monitored in the different solutions. The total Al will be detected by the in-plant sap sensor and a calibration equation for signal readout and concentration will be developed for low pH soil (4-5), and mid-range (5.5 to 6) and a high pH (6.5-7.5)) acid soil condition in the greenhouse or field. Tasks for **objective 2** includes Sensor calibration of Dirac Point Shift. The chemical agent in the in-plant sap will react with the OH^- at certain pH level and the different Al forms (Al_m^+) , will cause constant voltage and current (V_D and V_G, I_{DS}) change with the change of charge density on MXene-graphene surface. Moreover, changes in the relative amount of positive and negative charges could cause Dirac point shifting. After signal change (Dirac point shift) was characterized by the total Al and its key chemical forms concentration at different pH levels for the in-plant Al sap sensor. Based on the signal change, we can infer the concentration of the target chemicals, which can be compared and correlated with the standard soil test and plant sap analysis result for real-time soil acidity and Al toxicity in plant assessment. Point shift (i.e., the valley of the "V-shape" curve) for wheat plant sap and the Al toxicity detection in different pH conditions will be calibrated by investigating the measurement error between the controlled solution and the actual extracted wheat plant sap. The calibration factor/coefficient of the total Al and Al species concentration reading in ppm based on the standard soil test and plant sap test will be measured by Co-PI Strawn on ICP-AES (MDL ~0.001 mg/L). Tasks for **objective 3** is to Validation of In-situ plant Al plant sap sensing in the two lime field trail directed by Co-PI Schroeder. The first lime trail was established in the fall of 2016 in Potlatch, ID. The site includes 0, 1, 2 and 3 ton/A lime rates with each treatment being replicated four times. Individual plots measure 8 ft wide x 100 ft long. A second site will be established near Moscow in 2023 using the same experimental design. The soil samples from our trial sites and testing for soil pH, soluble aluminum and a number of other measurements at 3 in increments to a depth of 12 in will be collected to validate the effectiveness of the developed in-plant Al sap sensing. The agronomic measurements such as plant height and tiller count (for cereal crops) and will harvest to obtain grain yield, test weight, and protein content to evaluate the lime treatment performance. The USDA Cook Agronmoy Farm with three pH levels that ranged from low pH soil (4-5) to mid-range (5.5 to 6) and a high pH (6.5-7.5)) acid soil conditions directed by Collaboartor Huggins will be extended for field testing in 2025-2026. The in-situ plant Al sensor will be deployed to the field for testing the optimal power consumption, data collection frequency (diurnal pattern from every 1 second to 1 hour) and the spatial distribution (three pH zones with 5 replicates) and other environmental factors. Thus, the in-plant Al sap sensor will be validated with the in-field lime trial research in different soil acidity conditions, and will provide insights for Al toxicity in plant and its effects on the crop yield and quality and its potential in-season site-specific precision amendment.

Duration: 3 years: 2023-2026. The proposal is intended to produce preliminary data for pursuing federal funds, particularly, develop in-plant sap sensor network and coupling with multimodal aerial imaging for site-specific crop management and crop yield/quality improvement, involve growers and their on-farm trials in Idaho for economic benefit evaluation.

Cooperation/Complementation:
UI: Zachary Kayler, Assistant Professor, Soil and Water Systems. **USDA-ARS:** Dave Huggins, Northwest Sustainable Agroecosystems Research Soil Scientist. MST: Chenglin Wu, Assistant professor in Nanosensor and Materials Scientist.

Anticipated Benefits/Expected Outcomes and Transfer of Information:

The calibrated in-plant Al sap sensor will be validated with the in-field lime trial research at Idaho and USDA CAF Farm in different soil acidity conditions, thus the in-situ plant Al sensing data and its spatially-correlated total Al over time can be fused with weather data and soil map, multi- and hyperspectral remote sensing data, agronomic data and final yield data in the same filed, which will provide insights for Al toxicity in plant and its effects on the crop yield and quality and its potential in-season site-specific precision lime amendment. The research outcomes from this study will benefit agronomy, plant biology society and the precision agriculture research community. They will be integrated into education, training and outreach activities as briefly described below to maximize communication of the information obtained from this project nationally and internationally, including 1) written publications (at least 2 manuscripts) to be submitted to quality peer-reviewed journals based on the project findings during the project period and within two years past the ending date of the project; 2) presentations to be made at technical symposia and professional conferences, 3) PI teaches course ASM305 Precision Agriculture. The proposed novel plant sensor technology will be introduced as an examples into the courses; 5) field demonstrations at Dryland field days (DFD) for farmer with new tools for wheat breeding, wheat diseases and Plant Diagnostic. This project, once awarded, will allow us to continue to show the public with new precision Ag technology.

Literature Review:
Soil health is soil's capacity to perform agronomic functions including sustainable production of crops and animals while maintaining and improving the environment (Lal 2021, 2011). Soil health is strongly linked to climate change and human health (Rumpel 2019). Aluminum (Al) is the most abundant metal in earth crust and comprises 7% of it. Under acidic conditions (pH < 5.0), Al is solubilized into a toxic trivalent cation, Al^{3+} (Foy et al., 1978, Taylor, 1991). In many agriculturally important plant species, the presence of only micromolar concentrations of Al^{3+} can result in the inhibition of root growth within minutes or hours (Kochian, 1995). Al toxicity inhibit Root growth inhibition and hinder the water and nutrient uptake in plant (Ca, Mg, P, K, Mn, Fe, B, etc.) and thus reduce the crop yield (Shetty 2021, Sade 2016). Thus, continuous monitoring of nutrient availability in soil responsive to environmental variations and the uptake efficiency during growth of plants is critical for soil amendments and crop management including soil acidity monitoring and remediating plant Al toxicity. The microfluidic and microsystem with integrated sensors has recently been explored for in-situ soil nitrogen sensing (Garland 2018, Xu 2017, Ali, 2016, 2017, 2019), leaf water vapor deficit (Yin 2021), and in planta nitrate Sensor (Ibrahim 2022, Dong 2017, Jiang 2014, 2017) respectively. However, there are soil acidity induced Al toxicity in plants detection for nutrient uptake and plant tolerance impact study has not been reported yet. It is essential to gain the knowledges of soil acidity and Al toxicity in plant before it's 'subclinical' deficiencies or visual symptom occurs for potentially in-season correction of Al toxicity in an efficient precision manner.

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FY2024

COMMODITY COMMISSION BUDGET

Principal Investigator: Johnny Li

Allocated by ____________________ *(Commission/Organization)*	during FY2022	$	-
Allocated by ____________________ *(Commission/Organization)*	during FY2023	$	-

REQUESTED SUPPORT: Budget Categories	*Awarded for FY2023*	*Requested for FY2024*
(10) Salary *(staff, post-docs, e NOTE: Faculty salary/fringe not allowed*	$ -	$ 16,250
(12) Temporary Help/IH	$ -	$ 1,800
(11) Fringe Benefits	$ -	$ 742
(20) Travel	$ -	$ 472
(30) Other Expenses	$ -	$ 3,200
(40) Capital Outlay >$5k	$ -	$ -
(45) Capital Outlay <$5k	$ -	$ -
(70) Graduate Student Tuition/Fees	$ -	$ 7,896
TOTALS	$ -	$ 30,360

TOTAL BUDGET REQUESTED FOR FY2024: $ 30,360

BREAKDOWN FOR MULTIPLE INDEXES: Budget Categories	*Li*	*Strawn*	*Schroeder*	*(Insert Co-PI Name)*
(10) Salary *(staff, post-docs, e*	$ 16,250	$ -	$ -	$ -
(12) Temporary Help	$ -	$ 1,800	$ -	$ -
(11) Fringe Benefits	$ 585	$ 157	$ -	$ -
(20) Travel	$ 472	$ -	$ -	$ -
(30) Other Expenses	$ 1,200	$ 2,000	$ -	$ -
(40) Capital Outlay >$5k	$ -	$ -	$ -	$ -
(45) Capital Outlay <$5k	$ -	$ -	$ -	$ -
(70) Graduate Student Tuition/Fees	$ 7,896	$ -	$ -	$ -
TOTALS	$ 26,403	$ 3,957	$ -	$ -
			Total Sub-budgets	$ 30,360

Budget Justification

$	16,250	10-Graduate Student: 65% of graduate stipend
$	1,800	12-IH summer field help supervised by Dr. Strawn: ($15/hr x 120 hrs/worker = $1,800) **Fringe rates: Staff = 42%; IH= 8.7%; Student= 3.6%*
$	742	11-Graduate student @ 3.6%= $585; IH @ 8.7%= $157 *Per Diem= $55/day In-State; Mileage= $0.655/mi*
$	472	20-) Field trial site visits: 60 mi/trip @ $0.655/mile x 12 = $472
$	3,200	30-$1,200 for PI Li's prototype testing of in-plant sap sensor with in-lab calibration b) $2000 for PI Strawn's greenhouse cultivation and sample analysis: $ 10/sample x 20 = $200 for soil KCl extractions and analysis; c) $25/sample x 20 = $500 for Plant digest and analysis; d) Greenhouse study is about
$	-	(40-Insert Capital Equipment description)
$	-	(45-Insert Capital Equipment under $5K description)
$	7,896	70- 65% Graduate student tuition *$12,050/YR= Tuition, Fees and SHIP*