

BIOAG PROJECT FINAL REPORT

TITLE: Rapid sensing of dairy manure nutrients for precision applications in agricultural production.

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KEY WORDS: Dairy manure, Precision application, Nutrient composition, Near infrared spectroscopy (NIRS), Key spectral bands, rapid sensors.

ABSTRACT: The overall goal of this research project is to identify the optical sensing based spectral bands for rapid determination of manure nutrient to drive precise manure utilization on agricultural land. Excess manure application can adversely affect water quality, while under-application lowers crop yield potential. Precision application of manure requires information on its nutrients but the existing reliable nutrient determination methods are unsuitable for real-time applications. This project is evaluating the potential of near infrared spectroscopy (NIRS) for determination of nutrients composition of dairy manure, as a first step towards development of a precision manure application system. Manure was collected from different dairy farms to determine effective spectral bands for predicting available nutrients (N and P) in the manure with reference to typical lab methods. Spectral data were processed using multivariate statistical methods to identify nutrient specific key spectral bands necessary to develop a low-cost portable nutrients sensing device. This technology will enable farmers to precisely apply manure in the field at desired agronomic rates. The long-term impacts from commercialization and adoption of NIR sensor based precision manure application will be the improved protection of water quality and crop yield, both of which promote sustainable organic farming.

PROJECT DESCRIPTION:

Near infrared spectroscopy (NIRS) is a rapid, non-destructive method of composition analyses and is commonly used in agricultural plants and produce quality evaluations. NIRS quantifies change in reflectance of a sample, typically exhibiting linear proportional to varying nutrient concentrations, in ~700 to 2500 nm region of electromagnetic spectrum. The benefits of NIRS technique include acquiring spectral signatures without any sample preparation or use of additional chemicals, hence no chemical wastes. Additionally, variants of portable NIRS are available and appropriate use of any of such units can simultaneously determine multiple sample constituents. Since the overtone and combination bands of C-H, O-H and N-H groups are the main molecular vibrations in the NIR region, NIR spectral signatures can be used to predict concentrations of chemicals containing these bonds. Chemical descriptors like dry matter, organic carbon, total Kjeldahl N (TKN), NH₄-N, and organic nitrogen can potentially be directly predicted using NIR spectral data as has been shown in previous studies.

Previous manure nutrient estimation studies using NIRS, however, have been conducted in laboratories by scanning samples under stationary conditions. Most of these studies conducted tests under wide ranges of spectral bands (i.e. between 1000 to 2500 nm) but were not detailed enough to aid in establishment of suitable bands for predicting specific manure nutrients (such as N, P). Therefore, additional research was needed to fully utilize NIRS sensing technique for real-time manure nutrient quantification, which is necessary for variable rate manure application under field conditions.

The central hypothesis, of this research, is that determination of spectra of manure-nutrients using NIRS will lead to identification of nutrient-specific spectral bands necessary for custom-development of an affordable, miniaturized, and non-destructive sensing module. Integration of such sensors with variable

rate control technology on existing farm equipment will lead towards optimal manure delivery to improve soil quality without adversely affecting the ecosystem.

In order to develop a custom manure-nutrient sensor, which was the focus of this project, a real-time manure nutrient analysis using NIRS was needed to be coupled with suitable and effective computational algorithms. Such algorithms were needed to be robust to effectively estimate key nutrient levels from heterogeneous and complex manure, which introduce substantial nonlinearity in the response. The latter thus was also a key element of this project.

OUTPUTS

- Work Completed:

- **Experiment 1: Manure constituent sensing using diluted samples from single farm**

- Our goal in Experiment 1 was to develop a protocol for identifying key spectral bands in NIR region for manure nutrients determination. In this experiment, key spectral bands were determined under two spectra acquisition conditions: i) manure samples in stationary condition, and ii) manure samples in moving conditions (sample continuously mixed manually). Ten different manure samples were prepared by diluting (1.2–56.0 times) stock manure sample (fresh solid manure from barn, total solids = 13.7%). The prepared manure samples were stored in flat plastic bottles (100 mL capacity) and polyethylene bags (100 mL) for spectra acquisition. Five spectra were collected from each sample thus, a total of 100 spectra (in the range of 700–2500 nm) were collected using 20 samples (10 plastic bottle samples, and 10 polyethylene bag samples). Spectral data were normalized, binned (25 nm) and stepwise multiple linear regression was performed to extract pertinent spectral bands. The dimensionality of dataset was further reduced by principal component analysis. Robustness of selected spectral bands was evaluated using linear (partial least square regression (PLSR)) and non-linear regression models (support vector machine regression (SVMR) and artificial neural network regression (ANNR)).

- Under stationary conditions, spectral bands comprising 713.0, 740.6, 768.6, 964.7, 1022.9, 1144.7, 1175.1, 1295.5, 1532.7, 1849.5 nm were identified as the most relevant for determining dairy manure nutrients (nitrogen and phosphorus). Amongst the three prediction models, ANNR consistently better predicted nutrients with average R^2 of 1.00 for total ammonia nitrogen (TAN), orthophosphate (OP), total nitrogen (TN), and total phosphorus (TP). The respective prediction models had average RMSE of 5, 10, 36, 12 mg/L for TAN, OP, TN and TP.

- Under moving conditions, spectral bands comprising 713.0, 964.7, 993.6, 1144.7, 1265.5, 1295.5, 1355.3, 1444.4, 1849.5 nm were identified as the most relevant for determining dairy manure nutrients (nitrogen and phosphorus). Five spectral bands were found common (713.0, 964.7, 1295.5, and 1849.5 nm) between stationary and manure flow conditions. Under manure flow conditions also ANNR was found robust among three evaluated models with average R^2 of 1.00, 0.99, 0.99, 0.99 for TAN, OP, TN and TP, respectively. The respective prediction models had average RMSE of 10, 14, 41, 29 mg/L for TAN, OP, TN, and TP.

- **Experiment 2: Manure constituent sensing using manure samples from different farms**

- Our goal in Experiment 2 was to determine the key spectral bands in NIR region for manure nutrients determination using manure samples from different farms and sources. A total of 39 dairy manure samples (source: lagoon, anaerobic digester, and barn) were collected from seven different dairy farms in Washington State, USA. An additional 41 manure samples were also prepared by

diluting original manure samples (2–3 times) and mixing 2–3 different original samples. This preparation procedure resulted in a total of 80 manure samples (40, 20, and 20 lagoon manure, anaerobic digester manure, and fresh manure samples, respectively). In this experiment, 480 spectra were collected under stationary condition from 80 manure samples stored in flat plastic bottle (200 mL). In addition to steps described in Experiment 1, the following two steps were added in protocol: i) use average spectra ($n = 6$) of each sample during data analysis, and ii) outlier removal from spectral dataset before evaluating three models. Spectral bands for TS, TAN, and OP were identified in this experiment.

The potential key spectral bands identified for TS were 1114.4, 1144.7, 1205.3, 1265.5, 1295.5, 1444.4, 1678.2, and 1935.7 nm. Similarly, spectral bands 740.6, 1083.9, 1114.4, 1265.5, and 1935.7 for TAN; and 908.7, 1175.1, 1205.3, 1235.4, 1265.5, 1325.5, and 1991.0 nm for OP were identified using proposed methods. During training, the ANNR model had the highest R^2 (0.74–0.94) and lowest RMSE compared to other two models for all the tested nutrients. For the test dataset, mixed performance was observed for three models. For TS test dataset, ANNR model ($R^2 = 0.80$, RMSE = 0.7) was found most robust followed by SVMR model ($R^2 = 0.80$, RMSE = 0.8). Similar performance (high R^2 and low RMSE) trends of three models were observed for TAN test dataset. However, for the OP test dataset, the SVMR ($R^2 = 0.67$, RMSE = 71) and the PLSR model ($R^2 = 0.68$, RMSE = 74) showed better performances compared to ANNR model ($R^2 = 0.59$, RMSE = 119).

The results obtained in this experiment (i.e. Experiment 2) were different compared to results obtained in Experiment 1. In Experiment 1, all the three models performed better than in the second experiment. The latter could be attributed to: i) the use of manure samples ($n = 20$) that were prepared by diluting (1.2–56.0 times) stock manure with distilled water, and ii) use of multiple spectra ($n = 5$) from same sample for training and testing without averaging them (which might have generated a set of highly auto-correlated samples). The composition of manure is highly variable depending on the animal breed, the type of housing, the amount of water added, the type and the age of the animals, the feeding rations, and the type and duration of slurry storage, which could have been contributed to this variable performance as well.

Prediction accuracy of all the three developed models for TS and OP were comparable with previous studies but the accuracy for TAN was lower compared to previous studies conducted with different livestock manures. The reason for low performances of developed models in the present study may be attributed to smaller sample set used for training and testing compared to previous studies. Additional studies with larger sample dataset (200–400 samples), including manure samples from different sources and from additional farms are recommended for validating these results. In summary, however, this research indicates significantly high potential for developing a NIR-based sensor for rapid sensing of manure nutrients content. In particular, the novel method developed for selecting key spectral bands suitable for dairy manure nutrients determination forms a strong foundation for building low-cost portable NIR sensors, which is critical for wide adoption by producers.

- Publications, Handouts, Other Text & Web Products: Based on the completed work, our team presented a paper at the 2016 annual meeting of the American Society of Agricultural and Biological Engineers (ASABE) at Orlando, Florida, in the summer, entitled “**Evaluation of near infrared spectroscopy for rapid sensing of dairy manure nutrients**”. We also are presenting a poster at the 2017 annual meeting of the ASABE in July 16-19 in Spokane, Washington, entitled “**Identification of potential near infrared spectral bands for rapid sensing of dairy manure nutrients**”. In addition, we

have submitted a refined and expanded version of presented work for peer review and publication consideration to “**Biosystems Engineering**” [*manuscript # YBENG_2017_15*] with a title “**Application of near infrared spectroscopy for rapid determination of dairy manure nutrients.**”

- Outreach & Education Activities: PIs have been presenting this concept and pertinent outcomes at several outreach extension events (e.g. invited seminar at WSU-Mt. Vernon R&E center). We also presented this work at the ‘Waste-to-Worth’ conference in April 18-21, 2017 in Raleigh, North Carolina and also at the Washington State University ‘2017 BIOAg Symposium’ on March 1, 2017.

IMPACTS

- Short-Term: This project has trained one Ph.D. graduate student (Iftikhar Zeb), through direct involvement in all the activities of the project. The findings are already being disseminated via: peer reviewed journal, presentations at national meetings, and extension events/conferences.
- Intermediate-Term: (1) Development of cost-effective rapid device for determining dairy manure nutrients levels, (2) Manure applications on agricultural land based on known concentrations of nutrients, promoting environmentally and economically sound farm practices, and (3) This work lays the foundation of a more comprehensive precision manure application technology.
- Long-Term: The outcomes of this project will aid our team and other researchers in development, testing and promotion of precision manure nutrient application technology on conventional and organic farm lands. Precision manure-nutrients application will promote environmentally sound farm practices, a key focus of USDA-NIFA, enhancing sustainability of organic farming, and improved livestock waste management on dairy operations, while improving soil quality and fertility. Overall, the technology will aid farmers to follow site-specific crop management that will reduce production costs and potentially reduce water and air pollution from excess manure (nutrient) applications.

ADDITIONAL FUNDING APPLIED FOR / SECURED: Our team applied for additional funding from “**the Organic Transitions (ORG) competitive grants program of the USDA National Institute of Food and Agriculture (NIFA)**”, titled “**On-the-go dairy manure nutrients monitoring system for precision applications in crop production.**” The review panel thought this was a great proposal and encouraged us to define how this technology differs from what is now available and consider submission to more appropriate NIFA programs, such as **Agricultural Engineering and Biosystems** or the **SBIR**. Early this year, we addressed the comments from previous review panel and submitted a new proposal to USDA-NIFA Agricultural Engineering program, titled “**Measurement device of manure-nutrients in real-time for precision applications in crop production fields.**”

GRADUATE STUDENTS FUNDED: This project did not fund any student but has trained/involved a Ph.D. graduate student throughout the project period.

RECOMMENDATIONS FOR FUTURE RESEARCH:

The composition of manure is highly variable depending on the animal breed, the type of housing, the amount of water added, the type and the age of the animals, the feeding rations, and the type and duration of slurry storage. Thus, additional studies with larger sample dataset (200–400 samples), including manure samples from different sources and from additional farms are recommended for validating results of the present study. **We expect these additional studies to lead to the building of prototype devices and further field evaluation before commercialization.**