Received: 5 July 2023 | Accepted: 6 October 2023

DOI: 10.1002/aaai.12164

SPECIAL TOPIC ARTICLE

The AIFS Institute: Building a better food system through AI

Ilias Tagkopoulos[1,2,3] | **Mason J. Earles**[1,4,5] | **Danielle G. Lemay**[1,6,7] | **Xin Liu**[1,2] | **Nitin Nitin**[1,8] | **Aaron D. Smith**[1,9] | **Tarek I. Zohdi**[1,10] | **Stephen F. Brown**[1]

[1]USDA-NIFA/NSF AI Institute for Next-Generation Food Systems (AIFS), Davis, California, USA

[2]Department of Computer Science, University of California, Davis, California, USA

[3]Genome Center, University of California, Davis, California, USA

[4]Department of Viticulture & Enology, University of California, Davis, California, USA

[5]Department of Biological and Agricultural Engineering, University of California, Davis, California, USA

[6]Agricultural Research Service, U.S. Department of Agriculture, Western Human Nutrition Research Center, Davis, California, USA

[7]Department of Nutrition, University of California, Davis, California, USA

[8]Department of Food Science and Technology, University of California, Davis, California, USA

[9]Department of Agricultural and Resource Economics, University of California, Davis, USA

[10]Department of Mechanical Engineering, University of California-Berkeley, Berkeley, California, USA

Correspondence
Ilias Tagkopoulos, USDA-NIFA/NSF AI Institute for Next-Generation Food Systems (AIFS), Davis, California, USA.
Email: itagkopoulos@ucdavis.edu

Funding information
AFRI Competitive, Grant/Award Number: 2020-67021-32855; National Institute of Food and Agriculture, Grant/Award Number: 1024262

Abstract

Our food system is complex, multifaceted, and in need of an upgrade. Population growth, climate change, and socioeconomic disparities are some of the challenges that create a systemic threat to its sustainability and capacity to address the needs of an evolving planet. The mission of the AI Institute of Next Generation Food Systems (AIFS) is to leverage the latest advances in AI to help create a more sustainable, efficient, nutritious, safe, and resilient food system. Instead of using AI in isolation, AIFS views it as the connective tissue that can bring together interconnected solutions from farm to fork. From guiding molecular breeding and building autonomous robots for precision agriculture, to predicting pathogen outbreaks and recommending personalized diets, AIFS projects aspire to pave the way for infrastructure and systems that empower practitioners to build the food system of the next generation. Workforce education, outreach, and ethical considerations related to the emergence of AI solutions in this sector are an integral part of AIFS with several collaborative activities aiming to foster an open dialogue and bringing closer students, trainees, teachers, producers, farmers, workers, policy makers, and other professionals.

INTRODUCTION

Throughout human existence, food has been much more than a necessity. It has been an art, a way of expression, a part of our cultural inheritance, and evolution. It is not a coincidence that almost every culture in antiquity deified food or its process: from Demeter and Ceres, to Freyr and Inari, agriculture and food have been revered and adored, with sacred ceremonies, such as the Eleusinian mysteries in Ancient Greece, celebrating agriculture and the cycle of life (Mark, 2012).

As our world became bigger and more interconnected, so did the challenges that our food system faced. How do you feed a planet of 10 billion people, eliminating distribution and access inequalities, while keeping production sustainable, less wasteful, and resilient to disruptions such as climate change and loss of biodiversity? Concomitantly, the waves of agricultural revolution over the past couple of centuries with industrialization, monocultures, fertilizers, and advanced technology for crop management, coupled with globalization of food supply and interconnected global markets, have enabled unprecedented growth opportunities. Artificial Intelligence (AI) is regarded as a unique opportunity to accelerate innovation in the broader food system in a way that can address inefficiencies and bridge gaps in our food supply chain.

AIFS shares this view, and pioneers efforts to apply AI technologies to each stage of the food system, leveraging data and models to improve efficiencies of the companies and workers, and the safety and health of the consumers of our food system as a whole. At the front end of the food system, we are using molecular breeding to accelerate desirable crop traits including nutrition. In agricultural production, we are leveraging large agricultural datasets and building models to advance precision agriculture, and are also building models to optimize indoor farming. For processing, we are developing machine learning models to enhance the inactivation of pathogens and improve process validation at processing facilities. In the knowledge discovery and synthesis realm, we are using Deep Learning models and the latest in Natural Language Processing to build knowledge bases that ingest knowledge from a plethora of sources and millions of published papers so that the food, ingredients, chemicals, and health areas are intimately and interoperably interlinked, mined, and used in applications such as diet recommendation systems and bioactives discovery.

RESEARCH CLUSTERS

AIFS has six research clusters (see Figure 1). Four of these (molecular breeding, agricultural production, food processing, and nutrition) are focused on discrete areas of the food system, whereas two more research clusters, core AI, and ethics are overarching. AIFS provides competitive funding for approximately 40 researchers that work in interdisciplinary projects to apply AI methodologies that advance AI infrastructure in food systems, promote human health, and help create a more resilient supply chain. Below are some of the project highlights for each cluster.

Molecular breeding is a technology that can accelerate the rate at which a new line of a cultivar can arise from precise selection of which crosses to make during plant breeding. With an aim toward improvements in plant traits such as nutrition and climate adaptations, the AIFS team is developing a toolkit for integrating nutritional quality and aroma traits into molecular breeding strategies. Furthermore, the molecular breeding teams develop high-throughput assays and screening large cultivar collections via imaging and rapid sensors, to screen targeted cultivars for targeted molecules, leading to models to predict molecular composition and quality, among other traits.

The *agricultural production* cluster aims to deliver low-cost and easy to access sensing and data solutions. It develops and tests in real-use conditions novel inexpensive wireless AI-enabled sensors for accurately measuring agriculturally relevant soil signals such as nitrate, ammonium, phosphate, potassium, and moisture. The cluster also develops an open-source Python library (AgML), that enables access to agricultural-specific machine learning datasets, benchmarks, pretrained models, and workflows (Choi et al., 2023). Researchers also adapt a highly sophisticated 3D biophysical crop modeling tool (HELIOS) as a machine learning generator for synthetic sensor data. Several teams are investigating the use of reinforcement learning and model-based controls for autonomous navigation of ground- and aerial-robots in complex 3D environments like vineyards and almond orchards.

In the area of *food processing*, our team has been developing AI-based framework and models to enhance food safety, reduce food spoilage, and improve understanding of the role of food structure in enhancing nutrition and health benefits of food. In the area of food safety, the research projects have focused on enhancing the detection of pathogens (Yi et al., 2023) (Ma et al., 2023), improving food processing technologies using digital twins and machine learning models to enhance the inactivation of pathogens and improve process validation. The results of these studies demonstrate that AI models for image detection and classification and spectral data analysis can improve the speed and specificity of detecting target bacteria in complex food systems and aid in validation of novel processing technologies for the inactivation of target pathogens. Other work includes the development

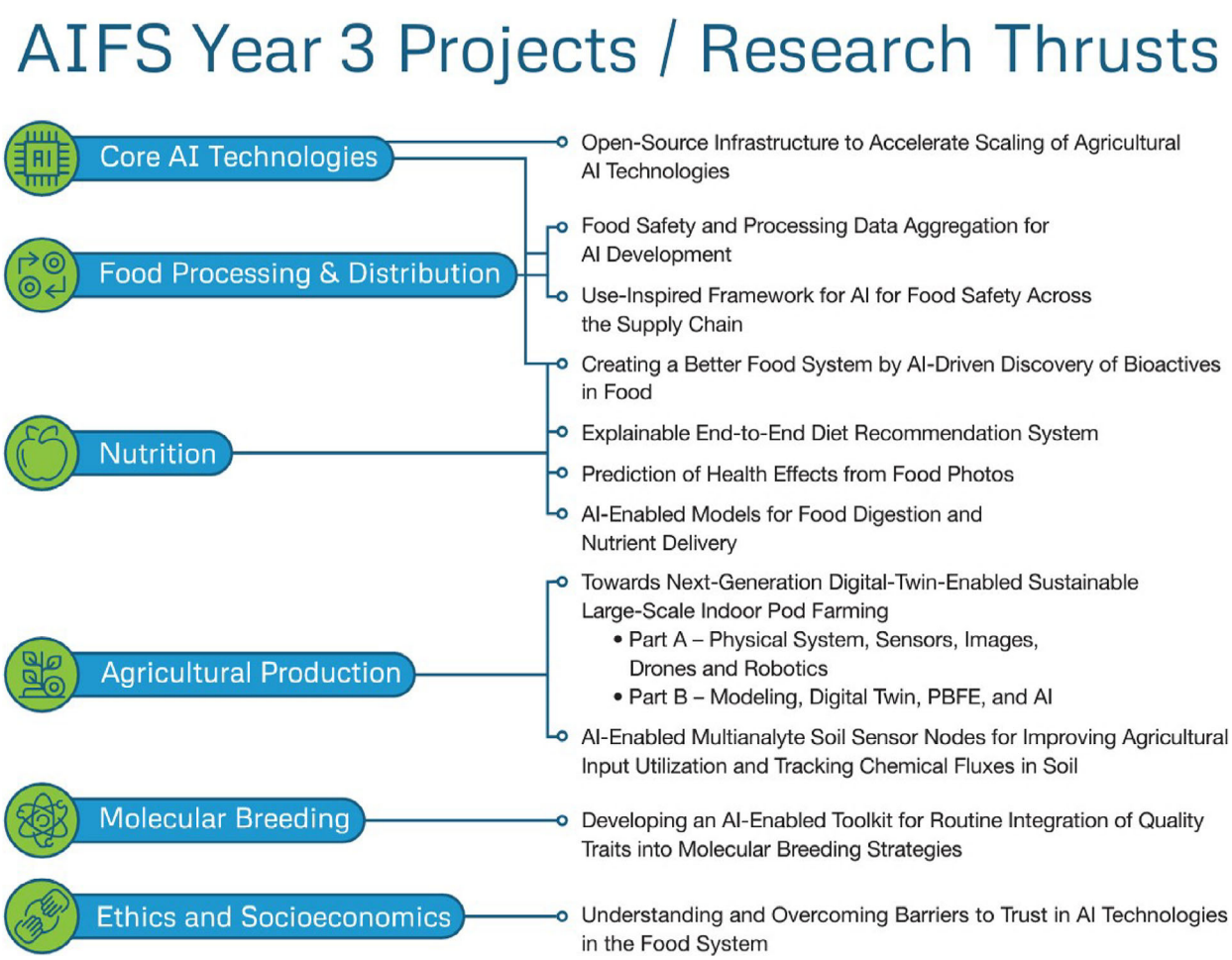

FIGURE 1 The six AIFS research clusters and the current projects that span across them. All projects are around the three AIFS thrusts of building the AI infrastructure for the food system, a resilient supply chain, and improving human health through food. AI, Artificial Intelligence; AIFS, AI Institute of Next Generation Food Systems.

of agent-based models to identify risk of the spread of pathogens in food facilities, an AIbased 3D printing model for bioinks for micronutrient release.and a digital twin for indoorfarming systems (Meng et al., 2023).

The *nutrition* cluster works in two main thrusts: developing AI methods to use food photos to track and assess what we eat in real-time, and to deliver dietary recommendations based on user preferences and nutritional status. The team is working toward a food "photo-to-ingredient" module and an "ingredients to health outcome" module, each of which will be needed in most computational systems in nutrition. The team has developed key resources such as the SNAPMe Benchmark Database for the evaluation of algorithms for computer vision in dietary assessment and the Food Atlas, a KnowledgeBase that uses deep learning, natural language processing, large language models, and other techniques to connect foods, ingredients, compounds, and health effects. Applications include the prediction of food composition after processing (Naravane & Tagkopoulos, 2023), algorithmic food matching and tolerance methods (Eetemadi & Tagkopoulos, 2023), automated ontology construction for food (Youn, Naravane, & Tagkopoulos, 2020), and causal prediction of dietary intervention efficacy in digestive diseases (Eetemadi & Tagkopoulos, 2021).

In *application-inspired and foundational AI*, the teams are researching applications in Federated Learning (FL) which is a distributed model training paradigm where clients collectively train a model while keeping their local data private. AIFS can serve the role of a central server because it has no direct conflict of interests with (industrial) entities. Explainability is crucial for the acceptance and adoption of AI-based solutions as in order to confidently use an AI system, it needs to be trusted, and in order to be trusted, it needs to be explainable. Concomitantly, the team is working in the field of AI-driven indoor farming, focusing on developing digital-twin technologies for the optimal optical design of sustainable large-scale indoor farming "pods," which consist of enclosed trailers with hydroponically grown plants, with energy supplied

by carefully controlled LEDs, whereby a continuous and constant supply of nutrient-rich water helps plants grow more consistently and while reducing inputs. The objective is to develop simulation tools to drive innovative solutions involving vertical farming panels of plants, utilizing LED light strip "walls," which provide crops with light from only the part of the spectrum required for growth.

The *workforce and ethics* team has developed an ethics framework around the principle that rules and compliance regulations are unlikely to solve the most difficult ethical challenges in AI. It is important that AI researchers and developers follow rules to, for example, protect the privacy of their data and honestly represent their products. Our ethics framework is built around a decisions and recommendations log in which researchers record their decisions and actions and their reasons for taking them with the goal that researchers make mindful decisions (Alexander et al, 2023). The framework emphasizes transparency, vigilance, and clear communication. In studying the ethical and socioeconomic challenges presented by AI in the food system, we ask three questions: (i) who wins and who loses from the technology? (ii) who bears the risks of bad outcomes? and (iii) who decides the answers to these questions? Workers on farms and in food processing plants will need to develop new skills to thrive in the labor market. Helping current workers and communities thrive is an important challenge we are working on.

EDUCATION AND PUBLIC ENGAGEMENT

Training and outreach is at the core of AIFS' mission, with the institute sponsoring various fellowships and training initiatives. One such initiative that targets researchers that are not from computer science is AIBridge, where researchers with limited prior programming experience get educated and then apply what they learn on AI projects related to food and agriculture. Over the past three years, hundreds of students have been trained on how to use Python, object oriented concepts, and machine learning libraries in practice, with some of them moving on to pursue this interdisciplinary field for their careers. The AIFS Career Exploration Fellowship Program is another initiative where companies mentor undergraduate students with internships, where students gain hands-on experience in an industrial setting. More broadly, AIFS regularly participates in conferences and competitions, creates various programs from K12 to postgraduate/professional level with various partners, and sponsors various events, such as the Apps for Food & Ag Hackathon and the Farm Robotics Challenge in which 19 teams from 12 universities built robotic solutions to farm tasks. All these initiatives have resulted in bringing together and training thousands of students and professionals from various industries and paths in life to collectively think and design a better, faster, and more resilient food system, with AI at its center.

COLLABORATIONS AND SYNERGIES

It takes a village to transform a system, and the food system is no different. Over the years, we have entered into close partnerships and joined activities across the Atlantic to co-sponsor DigiCrop 2022 with PhenoRob in Germany, and held joint activities with Fraunhofer ISE. Through the USDA's programs for funding 1890 (historically black land-grant) institutions, we have established collaborations with Delaware State University, Tennessee State University, Florida A&M University, Prairie View A&M University, and West Virginia State University. In terms of industrial partnerships, AIFS has also engaged with over 50 companies regarding the challenges facing the agriculture sector and opportunities for AI. From small startups to large CPG and ingredient companies, AIFS has partnered and co-sponsored projects in various topics that range from understanding the molecular composition of milk to creating AI tools related to knowledge organization and molecular discovery of key compounds such as polyphenols and terpenes, by using omics, flavor, and health effect predictors.

CONCLUSION

To conclude, through pioneering projects and transformative collaborations, AIFS is driven by a vision that transcends the ordinary. We aim to sculpt a society where wellness takes precedence over illness, a world where we nurture our health through accessible, nourishing food that confronts the very origins of diseases, notably chronic inflammation. Our commitment extends from the fertile fields to the very plates we eat from, all while honoring the sanctity of sustainable practices that safeguard our precious planet and its delicate ecosystems. We strive to be stewards of our inheritance, preserving these invaluable resources for the generations that will follow in our footsteps.

ACKNOWLEDGEMENTS

This work is supported by AFRI Competitive Grant no. 2020-67021-32855/project accession no. 1024262 from the USDA National Institute of Food and Agriculture. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of their affiliated institution or agency.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict.

ORCID

Ilias Tagkopoulos https://orcid.org/0000-0003-1104-7616

REFERENCES

Alexander, C. S., Yarborough, M., & Smith, A. (2023). Who is responsible for "responsible AI"?: Navigating challenges to build trust in AI agriculture and food system technology. Precision Agriculture 25(1): 146–85. https://doi.org/10.1007/s11119-023-10063-3

Choi, T., D. Guevara, G. Bandodkar, Z. Cheng, C. Wang, B. Bailey, M. Earles, and X. Liu. 2023. "DAVIS-Ag: A Synthetic Plant Dataset for Developing Domain-Inspired Active Vision in Agricultural Robots." arXiv: 2303:05764.

Eetemadi, A., and I. Tagkopoulos. 2023. "Algorithmic Lifestyle Optimization." *Journal of the American Medical Informatics Association* 30(1): 38–45.

Eetemadi, A., and I. Tagkopoulos. 2021. "Methane and Fatty Acid Metabolism Pathways Are Predictive of Low-FODMAP Diet Efficacy for Patients with Irritable Bowel Syndrome." *Clinical Nutrition* 40(6): 4414–21. https://doi.org/10.1016/j.clnu.2020.12.041.

Ma, L., J. Yi, N. Wisuthiphaet, M. Earles, and N. Nitin. 2023. "Accelerating the Detection of Bacteria in Food Using Artificial Intelligence and Optical Imaging." *Applied and Environmental Biology* 89(1), https://journals.asm.org/doi/full/10.1128/aem.01828-22.

Mark, J. "The Eleusinian Mysteries: The Rites of Demeter." *The World History Encyclopedia*, January, 2012.

Mengi, E., Becker, C. J., Sedky, M., Yu, S. Y., & Zohdi, T. I. (2023). A digital-twin and rapid optimization framework for optical design of indoor farming systems. Computational Mechanics: 1-13.

Naravane, T., and I. Tagkopoulos. 2023. "Machine Learning Models to Predict Micronutrient Profile in Food after Processing." *Current Research in Food Science* 6: 100500.

Yi, J., N. Wisuthiphaet, P. Raja, N. Nitin, and J. Earles. 2023. "AI-Enabled Biosensing for Rapid Pathogen Detection: From Liquid Food to Agricultural Water." *Water Research* 242: 120258. https://doi.org/10.1016/j.watres.2023.120258.

Youn, J., T. Naravane, and I. Tagkopoulos. 2020. "Using Word Embeddings to Learn a Better Food Ontology." *Frontiers in Artificial Intelligence* 3: 584784. Sec. AI in Food, Agriculture and Water. https://doi.org/10.3389/frai.2020.584784.

How to cite this article: Tagkopoulos, I., M. J. Earles, D. G. Lemay, X. Liu, N. Nitin, A. D. Smith, T. I. Zohdi, and S. F. Brown. 2024. "The AIFS Institute: Building a better food system through AI." *AI Magazine* 45: 89–93. https://doi.org/10.1002/aaai.12164

AUTHOR BIOGRAPHIES

Ilias Tagkopoulos, PhD, is the AIFS Director, AIFS Principal Investigator (PI), and a professor of Computer Science and the UC Davis Genome Center at the University of California-Davis. He has founded various companies that develop or leverage AI for healthy snacking, molecular discovery, and industrial optimization.

Mason J. Earles is assistant professor in the Departments of Viticulture & Enology and Biological and Agricultural Engineering at the University of California-Davis, and is AIFS co-PI and agricultural production cluster co-lead.

Danielle G. Lemay, PhD, is a Research Scientist at the USDA Western Human Nutrition Research Center in Davis, California. She is also an Associate Adjunct Professor with the Department of Nutrition and faculty member of the Genome Center at University of California-Davis and the AIFS nutrition cluster lead.

Xin Liu, PhD, is a Professor of Computer Science at the University of California-Davis and a co-PI and core AI cluster lead with AIFS.

Nitin Nitin, PhD, is vice-chair of the department of Food Science and Technology at the University of California-Davis, and is a co-PI and the food processing and distribution cluster co-lead with AIFS.

Aaron D. Smith, PhD, is the DeLoach Professor of Agricultural and Resource Economics at the University of California Davis, and is also the AIFS Ethics and Socioeconomics cluster lead.

Tarek I. Zohdi, PhD, is a distinguished professor in the Department of Mechanical Engineering at the University of California-Berkeley, and AIFS co-PI, education cluster lead, and food processing and distribution cluster co-lead.

Stephen F. Brown, Ph.D. is Associate Director of AIFS based at the University of California-Davis, and PI for AIVO, the AI Institutes Virtual Organization that is tasked to bring together the various NSF and USDA institutions.