Creating Intelligent Cyberinfrastructure for Democratizing AI: Overview of the Activities at the NSF-AI Institute ICICLE

Talk at TCS, Pune (Dec ‘23)

by

Dhabaleswar K. (DK) Panda
The Ohio State University
E-mail: panda@cse.ohio-state.edu
http://www.cse.ohio-state.edu/~panda

http://icicle.ai
Credits to all ICICLE Team Members!!

ICICLE Members Attending All-Hands-Meeting In-Person (Nov ‘23)
Outline

- ICICLE Vision and Goals
- Research Challenges Addressed
- Highlights of Selected Accomplishments
- Potential TCS Collaboration
- Conclusions
Computing has been evolving over the last three decades with multiple phases:

- Phase 1 (1975-): Scientific Computing/HPC
- Phase 2 (2000-): HPC + Big Data Analytics
- Phase 3: (2010-): HPC + AI (Machine Learning/Deep Learning)
Emergence of the Computing Continuum

1. Scientific Computing
2. Big Data & Data Science
3. Artificial Intelligence

HPC Systems & Data Centers

On Field Sensors
Edge & Near Edge
Clouds

HPC Systems & Data Centers

TCS-Pune (Dec ’23)
Societal Challenge (Example #1): Agriculture

- **Food security/sustainability in 2050**
  - 9.8B people, climate; 0.5x arable land per cap vs 1985
  - Wide gains in crop management needed (typical yields fall 3X below best practice)

- **Sustainable agricultural workforce**
  - The next generation of agriculture professionals will include engineers, computer scientists, data scientists

- **Democratization of digital agriculture capabilities**
  - Autonomous unmanned aerial vehicles, self-driving tractors and sprayers, fertilizer and seed recommendations
  - Big and small farms, staple and specialty crops, underrepresented communities
  - Privacy and ethical considerations
AI-Driven Digital Agriculture

https://ccag.tamu.edu/research-project/digital-agriculture/
Challenges in Designing AI-Driven CI for Digital Agriculture in Computing Continuum

Digital Ag
- CI for Autonomous, Self-Driving Farms
- Wrangling rapid data gen.
- Novel model architectures and datasets
- Open and Public Ag Services
- Adaptive AI at the Edge
- Privacy-aware Data Sharing

Conv. AI

Data: On Field Sensors
Models: Edge & Near Edge

Data/Models: Cloud
Data/Models: HECs

ICICLE-enabled Computing Continuum

TCS-Pune (Dec ’23)
Societal Challenge (Example #2): Animal Ecology

- **Basic science:** The focus of Animal Ecology is understanding the functioning and behavior of animals individually and in groups *in the context of environment* and evolution.

- **Science + translational:**
  - Monitoring, understanding, and protecting biodiversity of the planet
  - Monitoring and understanding the impact of changing habitats on animals that live in them

- **Translational:** biodiversity conservation and mitigating the impact of climate change
Challenges in Designing AI-Driven CI for Animal Ecology in Computing Continuum

Conv. AI

Data: On Field Sensors
Models: Edge & Near Edge

Data/Models: Cloud

Data/Models: HECs

ICICLE-enabled Computing Continuum

Resource+delay/model accuracy+analysis scope TRADEOFF
Societal Challenge (Example #3): Smart Foodsheds

- **Food Supply Chain Vulnerabilities**
  - Concentration contributes to bottlenecks, lack of resilience to disruptions

- **High Food Insecurity**
  - Supply chain decisions fail to account for impacts on food access, cost, availability

- **Food Waste**
  - Inefficiencies in food supply chains and food systems lead to 30-40% waste

- **Negative Environmental Footprint**
  - Farming and food system has major impacts on environment

- **Holistic Food Systems Planning is Difficult**
  - Data is difficult to access, not coordinated across sectors or food supply chain actors
Challenges in Designing AI-Driven CI for Smart Foodsheds in Computing Continuum

Smart Foodsheds

- Diverse data sources database federation
- Heterogenous food systems and actors
- Conversation agents and knowledge graph
- Food system planning Easy-to-use intelligent visual analytics

Conv. AI

- Data: On Field Sensors
- Models: Edge & Near Edge
- Data/Models: Cloud
- Data/Models: HECs

ICICLE-enabled Computing Continuum
Many more examples

- Smart Cities
- Smart Manufacturing
- Smart Transportation
- Real-time Surveillance
- Computational Medicine (Pathology, Radiology, ..)
Broad Challenge

Designing the next-generation intelligent cyberinfrastructure for a computing continuum with heterogenous resources that is usable in a plug-and-play manner by stakeholders to solve societal challenges?
The ICICLE Overview Video

The Video is available from

https://youtu.be/gNFk5tDTtoU
Objectives: Intelligent CyberInfrastructure for Computing Continuum

Use Inspired Science Domains

Digital Agriculture
Smart Foodsheds
Animal Ecology

ICICLE: Intelligent CyberInfrastructure with Computational Learning in the Environment

Systems AI Foundational Research for CI

Intelligent Cyber Infrastructure

CI for AI
AI for “CI for AI”

On Field Sensors
Edge & Near Edge
Clouds
HPC Systems & Data Centers

Emerging Computing Continuum
Participation:
14 Organizations, 33 faculty, 41 staff, (58 PhD, 16 MS, 16 undergrad, 6 K-12) students & many Collaborators
Collaboration: ICICLE and the Technology Innovation Hub (TIH) at the Indian Institute of Technology Bombay (IIT-B), India

<table>
<thead>
<tr>
<th>Digital Agriculture</th>
<th>Crop Health Modeling</th>
<th>Aerial Crop Scouting</th>
</tr>
</thead>
<tbody>
<tr>
<td>![USA flag] + ![India flag]</td>
<td>- Sense crop health and level context to predict crop yield</td>
<td>- CI for fully autonomous aerial systems</td>
</tr>
<tr>
<td>This research collaboration will contribute novel design paradigms for context-adaptive CI and aims to develop next-generation CI for Digital Agriculture including AI and machine learning methods targeting 3 core areas.</td>
<td>- Detect stressors and diseases for geographically diverse crops</td>
<td>- Simplify deployment of UAV in real fields to capture common crop health conditions</td>
</tr>
<tr>
<td>![Crop field image]</td>
<td>- Apply remedies with little human intervention via Internet of Things (IoT) and sensor systems</td>
<td>- Provide accurate maps that yield valuable insights for crop management</td>
</tr>
</tbody>
</table>

Privacy-Preserving Data Exchange

Create secure, trustworthy, and privacy-preserving platforms that connect farmers and allow them to share information and resources safely.

Building upon the existing ICICLE infrastructure, CI and AI capabilities, researchers will leverage contextual conditions in India for Digital Agriculture that differ from the United States to (1) expose brittle CI components, (2) make AI4CI more robust and expansive in the long-term, (3) devise principles that yield context-aware CI.
• Started on Nov 1, 2021
• Finished two years of the project, Starting Yr3
Outline

- ICICLE Vision and Goals
- **Research Challenges being Addressed**
  - Selected Accomplishment Highlights
  - Potential TCS Collaboration
  - Conclusions
Research Plan: Overall Vision

ICICLE
Intelligent CI

FUNDATIONAL SYSTEMS AI

CO-DESIGN FOR USE INSPIRED SCIENCE

INTELLIGENT CYBERINFRASTRUCTURE

CI FOR AI

AI FOR CI-FOR-AI

SOFTWARE ARCHITECTURE AND DESIGN

VISUAL ANALYTICS FOR CI AND AI EXPLAINABILITY

PRIVACY, ACCOUNTABILITY AND DATA INTEGRITY
Thrust: Foundational Systems AI

Components address CI complexity and heterogeneity for plug-and-play

Knowledge Graphs
- Multimodal KG to encode & reason rich data modalities (e.g., camera trap)
- Auto construction
- Interplay with LLM and knowledge-based QA

Model Commons
- MINT to support ICICLE use cases, KG, and models
- Precise profiling
- Flex composition
- Versioning and provenance

Adaptive AI
- Context-aware
- Efficient update
- User-friendly adaptation process
- Adaptation of foundation models, conversational AI

Federated Learning
- Heterogeneity
- Context-aware
- Privacy-preserving and robustness
- Going beyond classification (GNN, foundation models)

Conversational AI
- KG- and model-commons-aware
- LLM-powered
- Grounding LLMs to the context
- Hallucination reduction
- Complex reasoning
Thrust: CI4AI

Provides necessary CI to deploy AI throughout computing continuum and make it plug-and-play!

**High Perf. Training**
- High-performance communication libraries
- Gradient sparsification
- Exploiting data-, model-, pipeline-, and hybrid-parallel paradigms

**High Perf. Data Management**
- Unified storage of data, model and hyperparameters
- Data location transparency with migration
- Leveraging new hardware

**Edge Intelligence**
- Performance characterization of edge
- Optimize ML/DL inference on edge devices
- Profiling edge devices to improve quality of service

**AI-Adaptive Edge Wireless**
- High-throughput, reliable communications
- Predictable Wireless Comm. via Rateless-Coding & Multi-Modal/Path
- AI-adaptive edge wireless prototypes.

**Control and Coordination**
- Functional/Performance Interface Design
- Intelligent Resource Management with Tapis
- Hardening and Optimizing for Production-ready Service

Thrust: CI4AI Provides necessary CI to deploy AI throughout computing continuum and make it plug-and-play!
Thrust: AI4CI

Enhances CI with AI for adaptive and field-optimized machine learning!

- **KGs & Model Commons for CI**
  - Investigate and survey existing datasets for CI optimization
  - Create new CI components to serve CI data and models for other ICICLE CI and AI4CI components
  - Edge-specific CI dataset distributed as KGs

- **Intelligent Modeling and Optimization**
  - Collection of baseline performance
  - Exploration of analytical metrics
  - Use and refinement of hybrid models in a design-space explorer for code optimization

- **Applications**
  - Application Selection and Performance Profiling
  - Building Performance Models
  - Designing Features for Applications, Frameworks, and Hardware

- **Middleware**
  - Develop a set of intelligent linear algebra kernels for sparse-matrix operations
  - Leverage data sparsity in all computational kernels.
  - Cross-layer Optimizations

- **Systems**
  - Resource allocation optimizer for ML training
  - Develop an optimizing middleware for ML inference placement based on our use cases.
  - Intelligent Wireless Communications

Thrust: AI4CI

Enhances CI with AI for adaptive and field-optimized machine learning!
Thrust: Privacy, Accountability and Data Integrity (PADI)

- PADI contributes to
  - ICICLE vision as *transparent and trustworthy* infrastructure for AI-enabled future
  - An ethically aligned infrastructure and workforce through an *AI ethics framework*

- PADI advances both technical and non-technical innovations and best practices that collectively contribute to a trusted environment
  - *e.g.*, where stakeholders (farmers, industry partners, etc.) are comfortable contributing data and AI models for ICICLE AI research (and more broadly for AI research).

- PADI addresses both research questions and issues of practice (project norms and practice)
Thrust: Visual Analytics
Co-Designing with use-inspired domains

Conv. AI

Data: On Field Sensors

Models: Edge & Near Edge

Data/Models: Cloud

Data/Models: HECs

ICICLE-enabled Computing Continuum
The Deliverable: The ICICLE Software Stack

END USER APPLICATIONS
- CONVERSATIONAL AI
- DATA VISUALIZATION
- INTERACTIVE NOTEBOOKS, CLI, SDK, WEB APP

WORKER AGENTS
- DATA TRANSFER
- RESOURCE PROVISIONING
- JOB SCHEDULING
- PERSISTENCE
- MESSAGE BROKER
- SQL
- NOSQL
- SYSTEMS & FILES
- STREAMS
- META
- APPS & FUNCTIONS
- JOBS
- KNOWLEDGE GRAPHS
- CONVERSATIONAL AI
- MODEL COMMONS
- HISTORY & PROVENANCE
- AUTHN & AUTHZ

HTTP FRONT END APIs
- FILE SYSTEMS
- AI DATABASES
- GIT REPOSITORIES
- CONTAINER REGISTRIES
- EXECUTION HOSTS

DATA
- HPC & CLOUD DATA CENTERS
- FIELD SENSORS
- ICICLE GATEWAY

MODELS
- MODELS
- CONTROLLER

RESEARCHERS & USERS IN THE FIELD

EDGE & NEAR EDGE
- EXECUTION HOSTS

TCS-Pune (Dec ’23)
Broader Impacts Backbone Network (BIBN)

BIBN is a consortium with the goal of democratizing AI!

Oversees activities towards broader impacts and engagement:

- Diversity Equity and Inclusion (DEI)
- Broaden Participation in Computing (BPC)
- Workforce Development (WFD)
- Collaboration and Knowledge Transfer (CKT)
Outline

• ICICLE Vision and Goals
• Research Challenges being Addressed

• **Selected Accomplishment Highlights**
  • CI/Software Released
  • Digital Agriculture
    • Semi-Supervised Learning for large agricultural dataset
    • Edge Inference
    • Cloud-to-edge middleware (aerial crop scouting and crop management)

• Potential TCS Collaboration
• Conclusions
CI/Software Components Released (so far)

**2023.04 Release (04/30/23)**
- **AI4CI**
  - HPC Application Runtime Predictor (HARP) v1.0
  - Intelligent Sparse Library (iSpLib) v1.0
- **Software and Reference Architecture**
  - Base ICICLE Tapis Software v1.3.0
  - Event Engine v0.2.0
  - Hello ICICLE Authentication Clients v0.0.1
  - Tapis Pods Service v1.3.0
  - CI Components Catalog v0.1.0
- **Animal Ecology**
  - Camera-Traps Edge Simulator v0.3.0
- **Digital Agriculture**
  - SoftwarePilot v1.2.5
- **Smart Foodsheds**
  - Persons-Projects-Organizations-Datasets (PPOD) Schema v0.9.1
  - Smart Foodsheds Visual Analytics (VA) Dashboard v0.1

**2023.06 Release (06/30/23)**
- **AI Foundations**
  - ICICLE Foodshed Parser v0.1
  - Species Classification using Multimodal Heterogeneous Context v0.1.0
  - Region2vec v1.0
- **Software and Reference Architecture**
  - Tapis Federated Authentication Service v1.3.4
  - ICICONSOLE v0.0.10
  - TapisCL-ICICLE v0.1.4
  - Tapis Pods Service v1.3.2
- **Animal Ecology**
  - Camera-Traps Edge Simulator v0.3.1
- **Digital Agriculture**
  - ICICLE Digital Agriculture Hub v1.0
  - Far-Edge Edge Simulator v1.0
  - In-Field Helper for Crop Scouts v1.0
- **Smart Foodsheds**
  - Persons-Projects-Organizations-Datasets_California (PPOD_CA) Knowledge Graph v23.06
  - Kroger Store Closure v0.1
  - Smart Foodsheds Visual Analytics (VA) Dashboard v0.2

[https://icicle.osu.edu/cyberinfrastructure/software](https://icicle.osu.edu/cyberinfrastructure/software)
CI/Software Components Released (so far)

**2023.10 Release (10/06/23)**

- **AI4CI**
  - HPC Application Runtime Predictor (HARP) v2.0
  - High Performance Computing Applications Dataset v1.0
- **Software and Reference Architecture**
  - iciflaskn v1.0
  - ICICONSOLE v0.8.0
  - TapisCL-ICICLE v1.0.11
- **Animal Ecology**
  - Camera-Traps Edge Simulator v0.3.2
- **Smart Foodsheds**
  - Smart Foodsheds Visual Analytics (VA) Dashboard v0.3

[https://icicle.osu.edu/cyberinfrastructure/software](https://icicle.osu.edu/cyberinfrastructure/software)
ICICLE Use-Inspired Science: Digital Agriculture

Co-Leads

Scott Shearer
Food, Agriculture and Biological Eng.

Christopher Stewart
Computer Science & Eng

Zichen Zhang

Jenna Kline
Ohio State University

John C. Chumley

Kevyn Angueira Irrizary

P. Sadayappan
University of Utah

Jinghua Yan
University of Utah

Hari Subramoni

Nawras Alnaasan

Erman Ayday
Case Western

Beth Plale
Indiana University

Alfonso Morales
University of Wisconsin

Artificial Intelligence for Cyberinfrastructure

Cyberinfrastructure for AI-Driven Digital Agriculture

Privacy-aware, Explainable AI, & Democratization

Stakeholder Engagement
The Application Domain Challenge (Digital Agriculture)

Computer Vision (CV) based classification scenarios are ubiquitous in use-inspired science domains such as Digital Agriculture.

Residue Cover on Soil Surface
Soil Aggregate Size
Wheat Development
Non-Uniform Emergence

Nitrogen Deficiency
European corn borer
Corn leaf aphid
Mexican bean beetle defoliation
The Data Labeling Challenge

- Data samples need to be fully labeled by an expert for training and evaluation.
- Datasets may be collected frequently and in large volumes (millions of unlabeled images).
- Labeling data by experts is a significant bottleneck.
- Supervised learning can be time-consuming, costly, and infeasible for certain applications.
The Computing Challenge

• Why do we need Parallel Training?
• Larger and Deeper models are being proposed
  – AlexNet -> ResNet -> NASNet – AmoebaNet -> ViT
  – DNNs require a lot of memory and a lot of computation
  – Larger models cannot fit a GPU’s memory
• Single GPU training cannot keep up with ever-larger models
• Community has moved to multi-GPU training
• Multi-GPU in one node is good but there is a limit to Scale-up (8-16 GPUs)
• Multi-node (Distributed or Parallel) Training is necessary!!
HARVEST (High-Performance ARtificial Vision Framework for Expert Labeling using Semi-Supervised Training)
Demo: Semi-Supervised Learning
Inference Scenarios

1. **Online vs. batch inference:**
   - Online Inference: used when real-time predictions are required
     • Latency: Lower latency is critical for real-time applications, and online inference focuses on minimizing the time it takes to process individual instances.
   - Batch Inference: employed for processing large volumes of data at once
     • Throughput: Batch inference focuses on maximizing throughput by processing many instances simultaneously, rather than prioritizing latency.

2. **Edge vs. HPC/Cloud inference:**
   - Inference on the Edge: limited resources and require low-latency responses
     • Latency: Low-latency responses are crucial in edge scenarios, as real-time predictions may be necessary for applications like autonomous vehicles or IoT devices.
   - Batch Inference: more resources available
     • Throughput: HPC/cloud systems can scale horizontally and vertically, allowing for increased throughput when processing large volumes of data.
Inference on Edge Devices

- The size of DNNs has significantly increased making it challenging to deploy on resource constraint environments.
- What is the expected performance in terms of latency for different DNNs on different edge devices (Orin, Nano, Raspberry Pi, etc)?
- Different edge inference frameworks (PyTorch, TensorFlow Lite, ONNX runtime, TensorRT etc.) yield significantly different performance for different DNNs.
- Quantization can be used to effectively increase inference speed and reduce memory footprint for edge inference [1].

Digital Agriculture will transform crop management by:

1. Sensing environmental conditions
2. Characterizing crop health at fine granularities
3. Autonomously delivering cost-effective treatments

Stakeholders include farmers and biologists—traditional agriculture professionals—and data scientists, machine learning experts, engineers, and HPC professionals.

ICICLE seeks to develop CI needed for all stakeholders to create, share, and process agricultural data effectively and efficiently.

In this context, AI will drive improvements in:

1. Autonomous, self-driving farms
2. Methods to wrangle the rapid growth of agricultural data
3. Data-driven and context-aware agricultural insights
4. Context-aware management and differential privacy
5. Managing open & democratized digital agriculture services
Digital Agriculture: Aerial Crop Scouting

**Aerial Crop Scouting:** In this workload, we seek to create *heat maps* that describe crop health for a field
- *Inform* self-driving tractors and sprayers to reduce the application of pesticide and fertilizer
- *Predict* crop yields for harvest and market timing
- *Identify* trends across farms, such as the introduction of resistant weeds

**Technology:** Unmanned aerial vehicles (UAV) capture high resolution images
- Flying low (15 ft above ground): 1 pixel -> mm

**Transformative:** At mm-granularity, stakeholders can detect biological phenomena invisible to satellites
- Soybean leaf defoliation caused by Japanese beetle

Courtesy of LaRue Farms Inc.
Demo: Cloud-to-Edge Middleware
Engagement with Other Organizations

- On-going discussions with several other AI Institutes
  - AIFARMS
  - AIIRA
  - AgAID
- Collaboration with TIH-Mumbai
- Interactions with industry
  - CNH Industrial
  - TCS (more next)
Outline

• ICICLE Vision and Goals
• Research Challenges being Addressed
• Selected Accomplishment Highlights

• **Potential TCS Collaboration**

• Conclusions
Multiple Rounds of Meetings and Visits

- Meetings with
  - TCS management
  - Dr. Srini, Raju, and Nilesh
  - On-site and remote
- Focusing on multiple angles
  - R & D
  - Training
<table>
<thead>
<tr>
<th>Components</th>
<th>Project Y1-Y2</th>
<th>ICICLE Proposed Y3</th>
<th>ICICLE Proposed Y4, Y5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Collection</td>
<td>3 OSU Research Sites</td>
<td>UAVs at Pace Port remote controlled over internet and/or with pre-loaded models; More data collection up to 5 TB; integrate ICICLE work on wireless networks;</td>
<td>Widespread in-situ and small and medium farm data collection</td>
</tr>
<tr>
<td>Data Pipelines</td>
<td>Largely Manual</td>
<td>End-to-end automated workflows with-in built Q&amp;A for images (fixed cams, selfie sticks, UAVs);</td>
<td>Automated, hardened &amp; high-quality workflows incl. sensors</td>
</tr>
<tr>
<td>Training/Testing</td>
<td>Learn best models &amp; hyperparameters.</td>
<td>Weakly-supervised labelling (WSL) with very weak labels (handwritten notes) and semi-supervised labeling (SSL) for very limited number of strong labels. Training with vision transformers (ViTs). Explore various quantization techniques for optimized edge inference</td>
<td>Training/Testing with multi-modal data incl. images and sensor data and integrated w/ model commons</td>
</tr>
<tr>
<td>Decision Making with Outcomes</td>
<td>Researchers show prediction accuracy</td>
<td>Crop maps delivered to farmers with confidence measures. Transporting trained models between cloud and edge (with appropriate quantization)</td>
<td>On-demand &amp; continuous analyses on apps at edge; fully-labelled for multiple data types</td>
</tr>
<tr>
<td>Community Outreach</td>
<td>Winter 2024 Extension Meetings across Ohio</td>
<td>Training material and dissemination plans</td>
<td>Evangelization through TCS</td>
</tr>
</tbody>
</table>
Outline

• ICICLE Vision and Goals
• Research Challenges being Addressed
• Selected Accomplishment Highlights
• How to Get Engaged?

• Conclusions
Designing Next-Generation CI through Co-Designing with Use-inspired Domains

Conv. AI

Data: On Field Sensors
Models: Edge & Near Edge

Data/Models: Cloud
Data/Models: HECs

ICICLE-enabled Computing Continuum
Potential for the ICICLE Solutions to be applied to more Verticals

- Smart Foodsheds
- Digital Agriculture
- Animal Ecology
- Health & Medicine
- Environment
- Communications & Collaboration
- Mobility, Machines, & Manufacturing
- AI for Social Good

ICICLE: Intelligent CyberInfrastructure with Computational Learning in the Environment

Emerging Computing Continuum

- On Field Sensors
- Edge & Near Edge
- Clouds
- HPC Systems & Data Centers
ICICLE Enabling Global Leadership in `Computing + AI’

• Integrate into the National CI Ecosystem

• Integrative and Interoperable

• Leverages existing recognized capabilities
  - Centers of Excellence, AI Institutes, Large Facilities

• Collaborative
  - Actively engaging CI experts, domain scientists,
  - AI/CI Users and developers

• Sustainable and Inclusive
  - Workforce Development, Broadening Participation,
  Collaboration and Knowledge Transfer
  - Benefits other institutes, large facilities, and all sciences
  beyond lifetime of award

Join Us!
## Acknowledgments to all ICICLE Participants (Faculty, Students and Staffs)

### Current Faculty
- E. Ayday, CWRU
- Y. Cai, OSU
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- P. Sharma, IU
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- A. Hyder, OSU
- DB. Jackson-Smith, OSU
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- H. Shen, OSU
- T. Ruemping, IC-Foods
- D. Siedband, IC-Foods
- M. Biggers, IU
- RJ. Ping, IU
- BA. Plale, IU
- J. Wernert, IU
- M. Abduljabbar, OSU
- K. Armstrong, OSU
- J. Chan, OSU
- C. Guzman, OSU
- W. Michel, OSU
- N. Savardekar, OSU
- C. Hoy, OSU
- T. Tomich, UC Davis
- J. Duarte, UC San Diego
- H. Ahn, OSU
- P. Chawla, OSU
- E. Goetz, OSU
- Y. Gu, OSU
- C. Khandelwal, TIH IITB
- T. Sharma, TIH IITB
- A. Thaduri, TIH IITB
- S. Zac, TIH IITB

### Current Staff
- M. Lange, IC-Foods
- T. Ruemping, IC-Foods
- D. Siedband, IC-Foods
- M. Biggers, IU
- RJ. Ping, IU
- BA. Plale, IU
- J. Wernert, IU
- M. Abduljabbar, OSU
- K. Armstrong, OSU
- J. Chan, OSU
- C. Guzman, OSU
- W. Michel, OSU
- N. Savardekar, OSU
- M. Abduljabbar, OSU
- K. Armstrong, OSU
- J. Chan, OSU
- C. Guzman, OSU
- W. Michel, OSU
- N. Savardekar, OSU

### Current Ph.D. Students
- P. Kousha, OSU
- Z. Li, OSU
- V. Pahuja, OSU
- R. Qiu, OSU
- E. Romero, OSU
- C. Tu, OSU
- Y. Tu, OSU
- S. Vallabhajosyula, OSU
- L. Waltz, OSU
- B. Wang, OSU
- X. Wang, OSU
- Y. Tu, OSU
- S. Vallabhajosyula, OSU
- L. Waltz, OSU
- B. Wang, OSU

### Current Masters Students
- R. Danhi, IC-Foods
- J. Cheng, OSU
- S. Deshmukh, OSU
- M. Han, OSU
- A. O’Quinn, OSU
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- J. Yang, OSU
- Q. Ding, TACC
- V. deBella, UW Madison
- M. Krempey, UW Madison
- D. Wang, OSU
- X. Wang, OSU
- Z. Zhang, OSU
- Y. Tu, OSU
- S. Vallabhajosyula, OSU
- L. Waltz, OSU
- B. Wang, OSU

### Current Undergraduate Students
- T. Chen, OSU
- KA. Irizarry, OSU
- M. Lieber, OSU
- E. Luo, OSU
- D. Venkataraman, OSU
- S. Shah, UT Austin
- A. Karunakaran, UW Madison
- M. Kuhn, UW Madison
- Y. Qu, UW Madison
- K. Sung, UW Madison

### Current International Students TIH – IITB
- A. Borkar, TIH IITB
- RM. Chitre, TIH IITB
- R. Katole, TIH IITB
- S. Khandelwal, TIH IITB
- T. Sharma, TIH IITB
- A. Thaduri, TIH IITB
- S. Zac, TIH IITB

### Current Undergraduate Students
- T. Chen, OSU
- KA. Irizarry, OSU
- M. Lieber, OSU
- E. Luo, OSU
- D. Venkataraman, OSU
- S. Shah, UT Austin
- A. Karunakaran, UW Madison
- M. Kuhn, UW Madison
- Y. Qu, UW Madison
- K. Sung, UW Madison

### Current Institute Evaluators (WFD)
- T. McKlin, TFG
- C. Wise, TFG
- T. McKlin, TFG
- C. Wise, TFG

### Past Staff
- C. Campbell, IU
- E. Rillof, IU
- P. Sadayappan, IU
- S. Gao, UW-Madison
- K. Pierce, TACC

### Past Faculty
- C. Hoy, OSU
- S. Sanders, IU
- A. Ivanovic, OSU
- M. Norman, UC San Diego
- H. Ahn, OSU
- P. Chawla, OSU
- E. Goetz, OSU
- Y. Gu, OSU

### Past Masters Students
- SR. Kalli, OSU
- H. Panday, OSU
- RR. Loka, UW Madison
- D. Sykes, UW Madison

### Past Ph.D. Students
- FB Saravi, CWRU
- MK. Rahman, IU
- T. Zhang, ISU
- A. Jain, OSU
- D. Suresh, OSU
- S. Raje, UW

### Past UG Students
- S. Ockerman, OSU
- KP. Sailaja, OSU
- C. Washington, OSU
- J. Kim, TACC

### Educational Fellows (2023)
- B. Alston, OSU
- TE. Feiten, UC
- A. Hingle, GMU
- C. Lucken, UC
- S. Wegner, UW Madison

### Past K-12 Students
- S. Ockerman, OSU
- KP. Sailaja, OSU
- C. Washington, OSU
- J. Kim, TACC
Thank You!