Superparamagnetic Nanoparticles in Exploratory Energy Research

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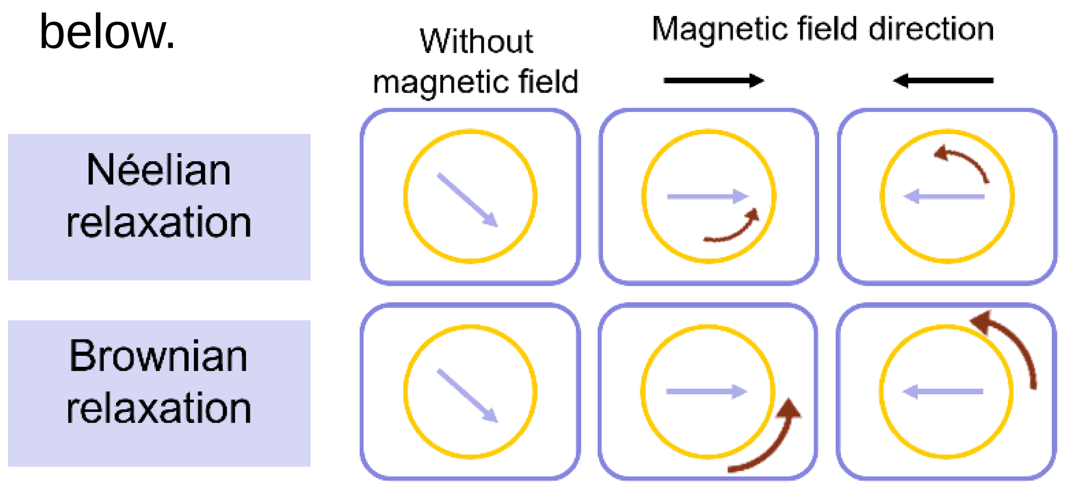
INTRODUCTION

- Fossil fuel dependency is a growing concern as climate change grows more rampant.
- Improving the efficiency of combustion engines can lower emissions, reduce demand, and promote a smooth energy transition.
- Non-magnetic nanoparticles have previously been used to reduce toxic emissions.
- Superparamagnetic nanoparticles (sPM-nPs) generate heat via 2 major mechanisms under an alternating magnetic field (AMF), as shown below.



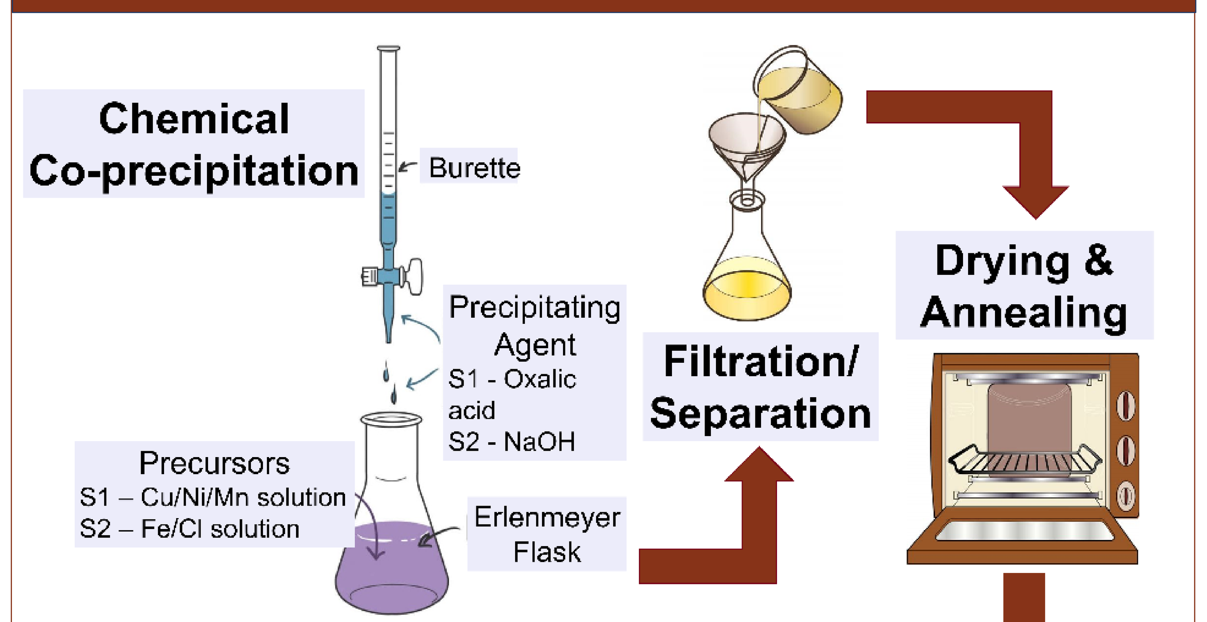
- Heat generation (specific absorption rate, SAR) is dependent upon the properties of the applied AMF and intrinsic properties of the particle [1].

$$SAR \propto H_0^2 f \frac{2\pi f\tau}{1+(2\pi f\tau)^2}$$

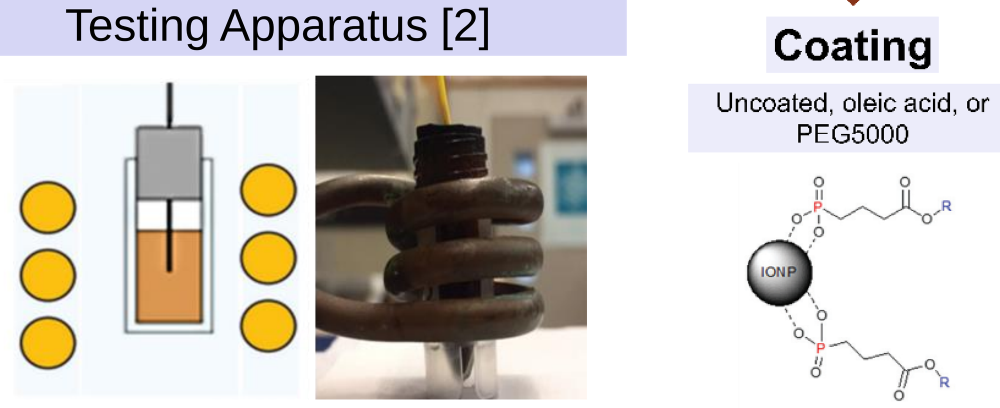
- sPM-nPs have been predominantly used in biomedical applications for localized hyperthermia

GOAL: Investigate and explore energetic and combustion characteristics of sPM-nPs.

METHODS



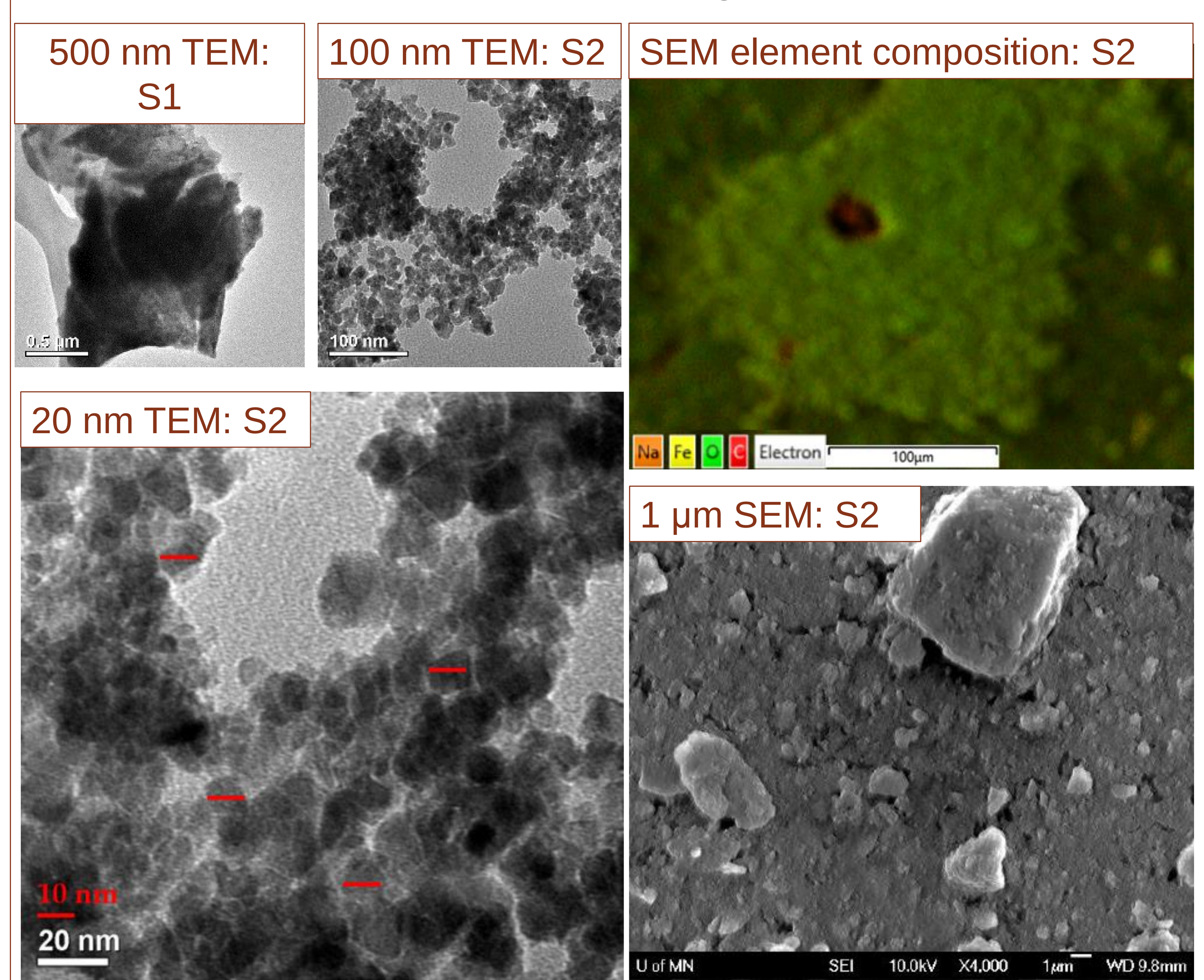
Testing Apparatus [2]



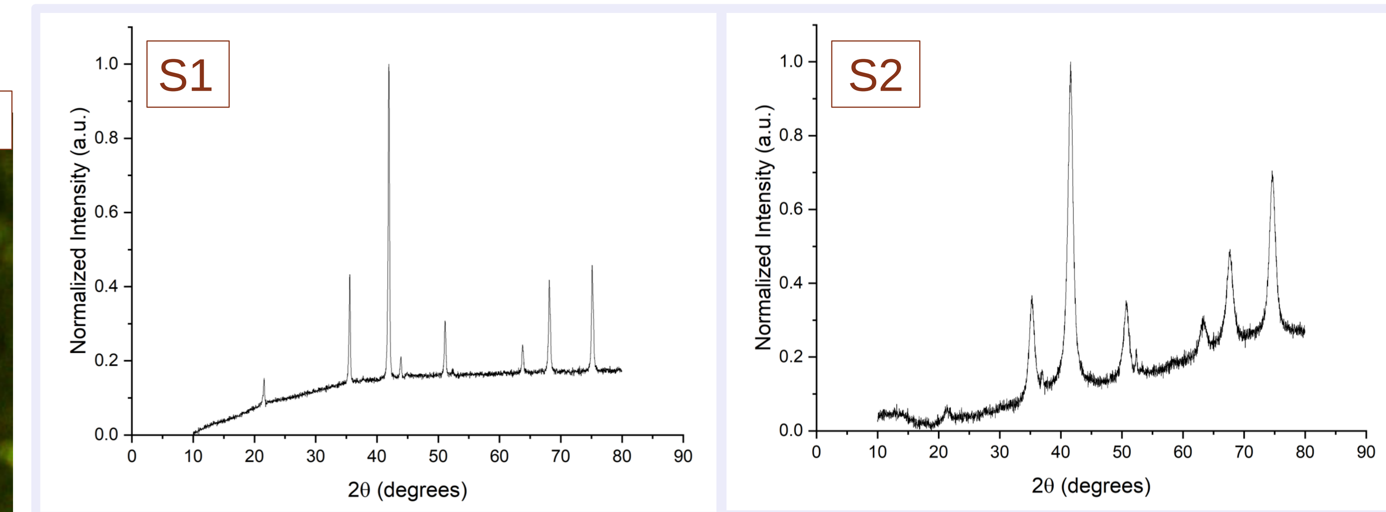
CHARACTERIZATION

Electron Microscopy (TEM/SEM)

BELOW: TEM and SEM images for S1 and S2



X-Ray Diffraction (XRD)

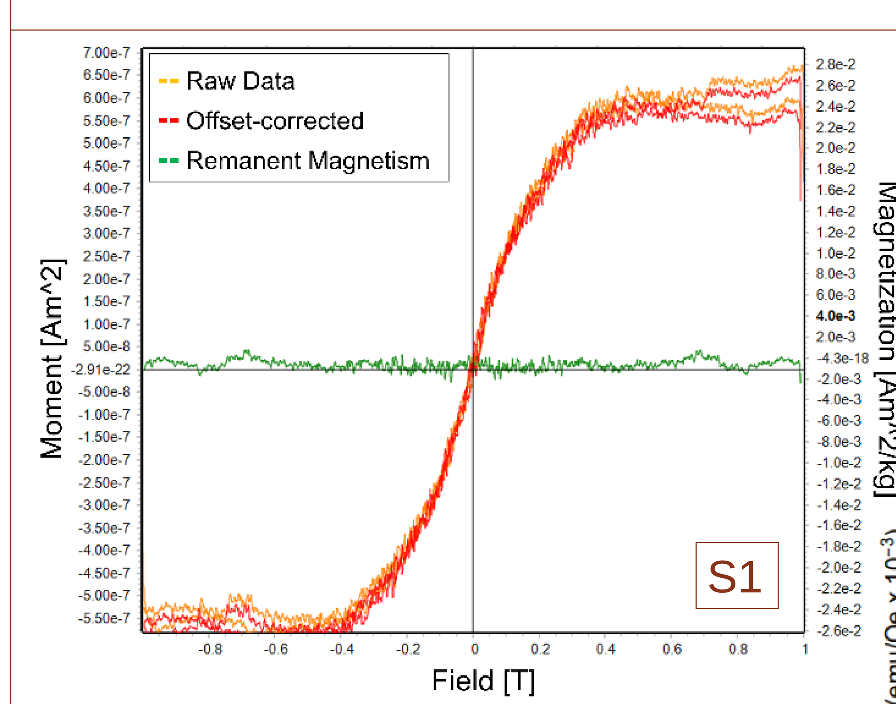


$$B(2\theta) = \frac{K\lambda}{L\cos(\theta)} \qquad \lambda = 2d\sin(\theta)$$

	Avg. Particle Size	Atomic Layer Distance
S1 - $Cu_{0.1}Ni_{0.9}Mn_2O_4$	47.005 nm	0.134 nm
S2 - Fe_3O_4	11.405 nm	0.252 nm

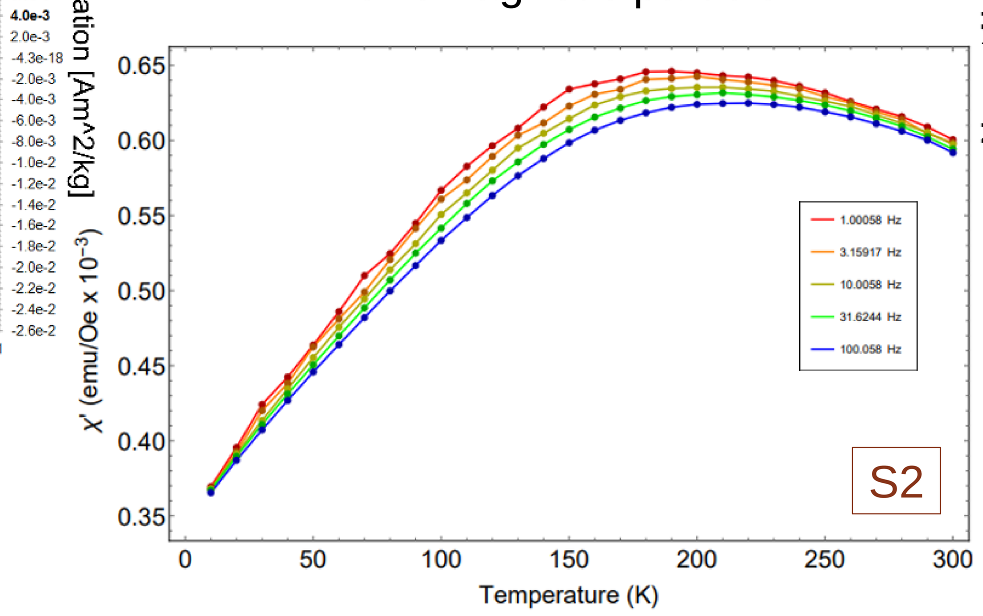
ABOVE: Average particle size (L) and atomic layer spacing (d), calculated by XRD via the shown equations, where K=1 and λ=0.179 nm. The particle size was also measured in ImageJ and visually confirmed by TEM images, shown to the left.

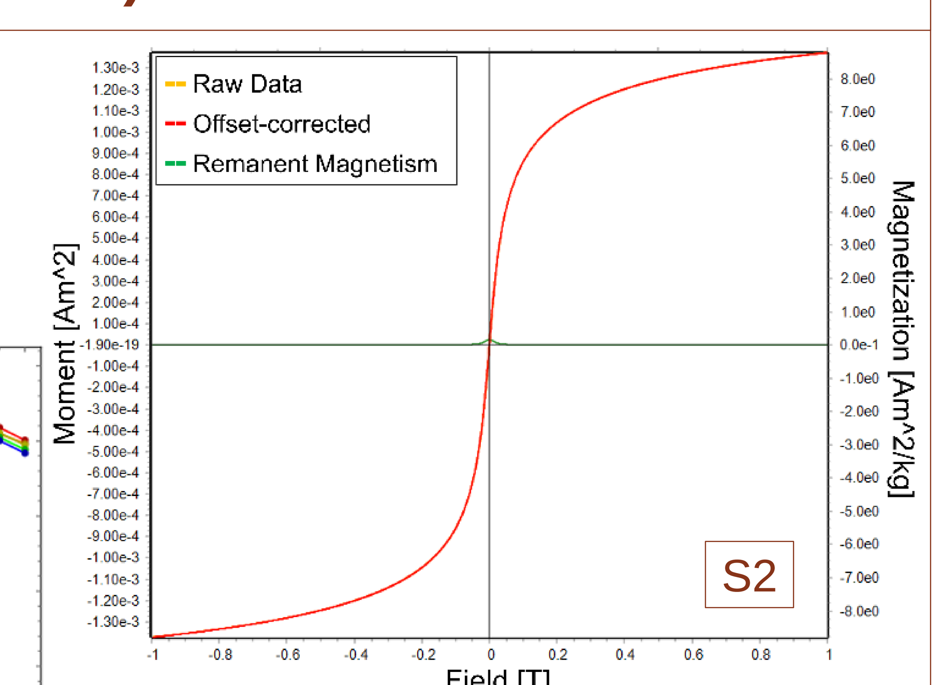
Vibrating Sample Magnetometry (VSM)



ABOVE: M-H curve for S1, showing weakly superparamagnetic behavior.

BELOW: Susceptibility curve for S2. Strong temperature and frequency dependence imply the superparamagnetic behavior of a ferromagnetic particle.





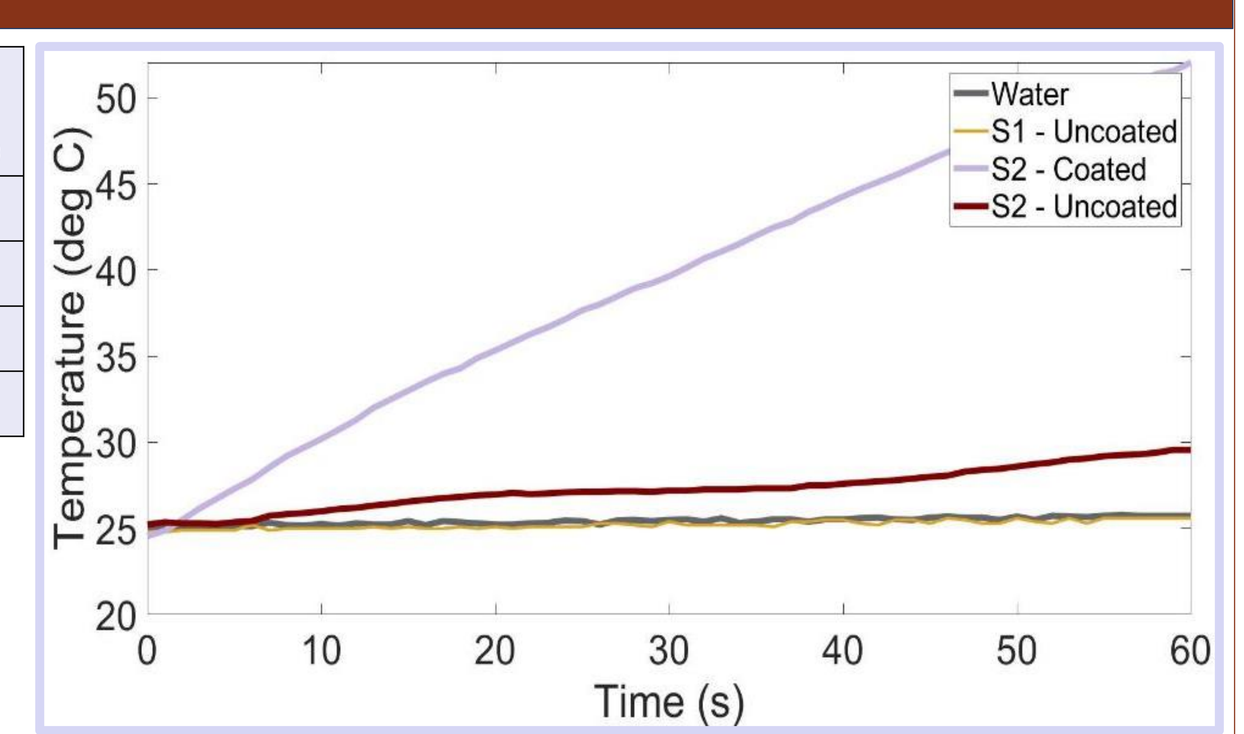
ABOVE: M-H curve for S2, showing a mixture of ferro- and superpara-magnetic properties.

APPLIED AMF TESTING

	Heat Rate (^{0}C/s)	Δ Temp (^{0}C)	Fe. Concen. (mg/mL)	SAR (W/g Fe)
Water	0.011	0.733	-	-
S1 - uncoated	0.012	0.8	-	-
S2 - coated	0.453	27.63	15.42	135.36
S2 - uncoated	0.068	4.73	2.14	187.48

$$SAR = (rate_s - rate_{H_2O}) * (\frac{C_{H_2O}}{Fe\ Concen.} * 1000)$$

ABOVE: Table summarizing results and SAR (relationship shown)
RIGHT: Plot of each sample's temperature while under an applied AMF (strength: 20kA/m, frequency: 360 kHz).



DISCUSSIONS

- Although weakly superparamagnetic, $Cu_{0.1}Ni_{0.9}Mn_2O_4$ (S1) was found to act as a heat sink, which literature agrees with [3]
- Fe_3O_4 (S2) shows great promise as a heat source due to falling under the critical diameter and a comparatively high SAR
- Characterization revealed impurities in S2
- Unwanted oxidation may have influenced composition, particle size, and hyperthermic properties
- Coating inhibited the SAR but was necessary for colloidal stability

Was the goal met? Yes.

FUTURE RESEARCH

Optimize coating materials and methods

- Limited impact on heating
- Long-term dispersion and stability in fuels
- Lower toxic engine emissions

- Investigate alternate compounds to enhance hyperthermic effects and limit toxic emissions (metallic doping of Fe_3O_4).
- Perform combustion testing with and without the sPM-nPs and measure performance.

ACKNOWLEDGMENTS

- Part of this work was as a visitor at the Institute for Rock Magnetism (IRM) at the University of Minnesota. The IRM is a US National Multi-user Facility supported through the National Science Foundation, Earth Sciences Division (NSF EAR-2153786), and by funding from the University of Minnesota (UMN).
- Also from UMN, we would like to thank the following for their invaluable contributions:
  - Dr. Jaqueline Pasek-Allen, under the direction of Dr. John Bischof, director of ATP-Bio
  - The Penn Research Group
  - Shepherd Laboratories

References

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