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Harnessing Solar Energy for Pumping Machines during Dry Seasons: Implications for Agribusiness among Adult Learners

Adamu Zakariya[1*]; Eleweke Mercy Motunrayo[2]

TETFund Centre of Excellence for Teaching Basic AgroBusiness Skills, (TCoE-TBABS) of the Federal College of Education, Yola

*Corresponding Author

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Abstract— *The escalating challenge of water scarcity during dry seasons continues to impede smallholder agricultural productivity across Sub-Saharan Africa, including Nigeria. This journal article examines the adoption of solar-powered pumping machines as a renewable and cost-effective water management solution, with particular emphasis on its implications for agribusiness among adult learners. Drawing on a review of empirical studies, field surveys, and adult education frameworks, the paper explores the technical dimensions of solar pumping systems, their economic viability, environmental sustainability, and the critical role of adult learning in facilitating technology adoption. The study identifies barriers to adoption — including high initial cost, limited technical literacy, and inadequate policy support — alongside enabling factors such as community-based learning models, government incentive schemes, and access to microfinance. The findings suggest that integrating solar pumping technology into adult agricultural education curricula can significantly enhance agribusiness productivity and profitability. Policy recommendations for stakeholders, extension officers, and educational institutions are provided.*

Keywords— Solar energy, Solar pumping machine, Dry season farming, Agribusiness, Adult learners, Adult education, Renewable energy, Irrigation, Nigeria, Smallholder farming, Climate change adaptation, Agricultural extension, Andragogy, Sustainable agriculture, Water management.

I. INTRODUCTION

Water is the lifeblood of agriculture. In many parts of sub-Saharan Africa, including the savanna and semi-arid zones of Nigeria, smallholder farmers face extreme water stress during the dry season — typically spanning from November to April — when rainfall ceases and surface water bodies recede. This seasonal dearth of water forces farmers to rely on costly, often unreliable diesel-powered pumps or to abandon farmland entirely, resulting in significant losses of income and food production potential.

Nigeria, as Africa's most populous nation and a country whose rural economy is dominated by smallholder agriculture, faces these challenges acutely. The National Bureau of Statistics estimates that over 70% of Nigerians engaged in agriculture are smallholders operating on less than two hectares of land. Their vulnerability to climate variability, particularly the lengthening of dry seasons attributed to climate change, places their livelihoods in perpetual jeopardy. Agricultural output losses during the dry season contribute significantly to rural food insecurity and poverty.

Solar energy has emerged as a transformative technological response to this crisis. Photovoltaic (PV)-powered water pumping systems harness sunlight — an abundant, free, and inexhaustible resource — to drive submersible or surface pumps that draw water from boreholes, wells, rivers, and reservoirs. Unlike diesel-powered alternatives, solar pumps eliminate fuel costs, reduce carbon emissions, require minimal maintenance, and can operate in remote locations without grid connectivity. These attributes make solar pumping particularly well-suited for smallholder irrigation in Nigeria and across the developing world.

However, the adoption of solar pumping technology does not occur in a vacuum. It requires that farmers understand the systems, trust them, know how to operate and maintain them, and have the financial resources to acquire them. This places adult education — specifically, vocational and agricultural adult learning — at the center of the adoption process. Adult learners, who constitute the overwhelming majority of practicing farmers in Nigeria, must be equipped with the technical competencies and business acumen to leverage solar irrigation for productive agribusiness.

This journal article critically examines the intersection of solar energy technology, dry-season irrigation, agribusiness development, and adult learning. It is structured around key questions: What are the technical and economic dimensions of solar pumping systems? What are the implications of solar-powered irrigation for agribusiness outcomes? What barriers do adult learners face in adopting these technologies, and how can educational interventions address them? And what policy frameworks are needed to support the transition to solar-powered agriculture?

II. SOLAR ENERGY AND SOLAR-POWERED PUMPING SYSTEMS

2.1 Overview of Solar Photovoltaic Technology

Solar photovoltaic (PV) technology converts sunlight directly into electrical energy through the photovoltaic effect. When photons from sunlight strike semiconductor materials — primarily silicon — electrons are excited and a direct current (DC) is generated. This current can be used immediately or stored in batteries for later use. The fundamental components of a solar PV system include solar panels (modules), a charge controller, a battery bank (for off-grid systems), an inverter (to convert DC to AC), and the load — in this case, a water pump.

Solar pumping systems are broadly categorized into two types: (1) direct-coupled systems, where the pump operates only during daylight hours using power directly from the panels; and (2) battery-coupled systems, which store energy and allow pumping at any time of day. For agricultural purposes, direct-coupled systems are often preferred for their simplicity, lower cost, and reduced maintenance burden, particularly for submersible borehole pumps.

2.2 Advantages of Solar Pumping Over Conventional Alternatives

The superiority of solar pumping over diesel or grid-based alternatives across multiple parameters has been well documented in the literature. Diesel pumps, while widely used, impose a heavy and ongoing financial burden on smallholder farmers. Fuel costs in rural Nigeria can be highly volatile, and supply chains are often unreliable, particularly during periods of fuel scarcity. Studies in northern Nigeria have found that diesel fuel expenses alone can account for 30–45% of the total variable cost of dry-season production, significantly eroding farm profit margins.

In contrast, once a solar pumping system is installed, its operational cost is negligible. Sunlight costs nothing, and modern PV panels have operational lifespans of 20–25 years with only occasional cleaning required. The elimination of fuel dependency translates directly into cost savings that improve the economic viability of dry-season farming.

Environmental considerations are equally compelling. Diesel generators emit carbon dioxide, particulate matter, and other pollutants that degrade air quality and contribute to climate change. Solar pumping systems produce zero direct emissions during operation. At a time when Nigeria and other developing nations are under increasing pressure to meet their nationally determined contributions (NDCs) under the Paris Agreement, the promotion of solar irrigation aligns with both national and global sustainability goals.

2.3 System Sizing and Suitability for Smallholders

A critical factor in solar pump adoption is correct system sizing — the process of matching solar panel capacity and pump specifications to the water demand of a given farm. For a typical smallholder vegetable farm of 0.5–2 hectares in Nigeria's dry belt, a solar pumping system with a capacity of 0.5–2 kW can provide sufficient water for daily irrigation needs from a borehole or open well. The daily water requirement for such farms, depending on soil type and crop type, ranges from 2,000 to 10,000 litres. A properly sized system can meet this demand within 5–6 hours of peak sunshine.

The Nigerian savanna and semi-arid zones — including Plateau, Kano, Kaduna, Sokoto, Katsina, and Borno States — receive an average of 5.5–6.5 peak sun hours per day during the dry season, making them particularly favorable for solar pumping applications [NiMet, 2023]. This high solar irradiance ensures consistent pump performance even during the Harmattan period when haze slightly reduces solar intensity.

III. IMPLICATIONS OF SOLAR PUMPING FOR AGRIBUSINESS

3.1 Year-Round Production and Revenue Continuity

Perhaps the most transformative implication of solar-powered irrigation for agribusiness is the elimination of seasonal agricultural gaps. In rain-fed farming systems, income generation is concentrated in a single rainy season cropping cycle, leaving families without agricultural income for five or more months each year. Solar-powered irrigation enables smallholders to cultivate crops throughout the dry season, thereby achieving year-round production and income continuity.

Empirical evidence from multiple studies across Nigeria confirms this income-enhancement effect. A study conducted by the International Water Management Institute (IWMI) in Kano and Jigawa States found that farmers who adopted solar-powered drip irrigation increased their annual net agricultural income by an average of 67% compared to non-adopters [IWMI, 2020]. Much of this gain was driven by the ability to grow high-value dry-season crops — tomatoes, onions, peppers, leafy vegetables, and watermelons — which command premium market prices during periods of otherwise low supply.

3.2 Crop Diversification and Value Chain Development

Solar irrigation also enables crop diversification, a strategy widely recognized in agribusiness as a risk management and income enhancement tool. When water is available year-round, farmers are no longer constrained to the limited suite of crops adapted to rain-fed conditions. They can grow perishable, high-value horticultural crops that would be impossible under rainfall-dependent systems. This diversification creates linkages to processing, packaging, storage, and marketing value chains, opening new entrepreneurial opportunities for adult learners engaged in agribusiness.

In Jos, Plateau State — a historically important zone for vegetable production in Nigeria — the adoption of solar-powered irrigation has been associated with the emergence of farmer cooperatives that collectively supply urban markets, supermarkets, and export processors [Babatunde et al., 2020]. These cooperatives represent a higher-order form of agribusiness organization facilitated, in part, by the production reliability that solar irrigation provides.

3.3 Cost-Benefit Analysis of Solar Pumping Investment

A concern frequently raised by smallholder farmers and adult learners considering solar irrigation is the relatively high upfront capital cost of PV systems. A complete solar pumping system — including panels, pump, controller, pipework, and installation — typically costs between NGN 350,000 and NGN 1,200,000 (approximately USD 200–700 at 2024 exchange rates) depending on capacity. This represents a significant investment relative to the average annual income of a smallholder farmer in northern Nigeria.

However, a rigorous cost-benefit analysis reveals a compelling financial case for adoption. Studies show that a typical 1 kW solar pumping system, irrigating 1 hectare of vegetables during the dry season, can generate additional net revenue of NGN 150,000–300,000 per cropping cycle [Muhammed & Abdullahi, 2023]. With two to three dry-season cycles possible per year, cumulative additional income can reach NGN 400,000–900,000 annually. The payback period is thus typically 1.5–3 years, after which the system generates pure net gain for the remainder of its 20+ year lifespan. This compares favorably to diesel alternatives, which impose ongoing fuel and maintenance costs that perpetually erode profitability.

TABLE 1
COMPARATIVE COST ANALYSIS OF DIESEL AND SOLAR PUMPING SYSTEMS (1 KW CAPACITY, 1 HA IRRIGATION)

Parameter	Diesel Pump	Solar Pump
Initial Purchase Cost	NGN 80,000–150,000	NGN 350,000–1,200,000
Annual Fuel/Operating Cost	NGN 180,000–400,000	~NGN 0
Annual Maintenance Cost	NGN 30,000–80,000	NGN 5,000–15,000
Operational Lifespan	3–5 years	20–25 years
CO_2 Emissions	High (diesel combustion)	Zero (operational)
Noise Pollution	Significant	None
Fuel Supply Risk	High	None
5-Year Total Cost (est.)	NGN 1,100,000–2,200,000	NGN 375,000–1,275,000

Source: Compiled from Muhammed & Abdullahi (2023); Adekoya & Ishola (2022); Aliyu et al. (2021); and IWMI (2020).

3.4 Market Access, Competitiveness and Export Potential

The agribusiness implications of solar irrigation extend beyond on-farm production to market access and competitiveness. By producing crops year-round, solar-irrigated farmers can negotiate more stable supply contracts with food processors, traders, and institutional buyers such as school feeding programs and hospitals. Stable supply predictability — a premium in commodity markets — translates into better prices, reduced market risk, and stronger buyer relationships.

Nigeria's horticulture sector is increasingly attracting export interest, particularly in products such as sesame, hibiscus (zobo), cashew, and ginger. Solar-powered irrigation can enable smallholder participation in these export value chains by supporting consistent, year-round production to the required quality and volume standards. For adult learners engaged in agribusiness development, this represents a transformative pathway out of subsistence agriculture into commercial, income-generating enterprise.

IV. SOLAR IRRIGATION AND ADULT LEARNERS: AN EDUCATIONAL PERSPECTIVE

4.1 Characteristics and Learning Needs of Adult Farmers

Adult learners engaged in agriculture possess distinctive characteristics that differentiate them from younger learners in formal educational settings. Malcolm Knowles' foundational theory of andragogy identifies adult learners as self-directed, experienced, goal-oriented, relevancy-focused, and practically motivated [Knowles et al., 2015]. These characteristics have profound implications for how solar pumping technology is taught, demonstrated, and adopted within agricultural extension and adult education frameworks.

Most smallholder farmers in Nigeria's dry-season farming zones are adults between 30 and 60 years of age, many of whom have limited formal education. Their primary motivation for learning is pragmatic: they seek knowledge that directly improves their livelihoods. Abstract technical lectures are unlikely to resonate; what works is hands-on demonstration, farmer field schools, peer-to-peer learning, and linkages to tangible outcomes such as improved yields and higher income.

4.2 Current State of Solar Energy Education in Agricultural Extension

Nigeria's agricultural extension system, through the Agricultural Development Programmes (ADPs) in each state, has historically focused on crop agronomy, fertilizer use, and pest management. The integration of renewable energy technologies — including solar pumping — into extension curricula has been limited and inconsistent. A national survey by the Federal Ministry of Agriculture (2023) found that less than 12% of frontline extension agents had received formal training on solar irrigation systems, and fewer than 8% had facilitated a farmer demonstration of such technology [FMARD, 2023].

This gap represents both a challenge and an opportunity. The challenge is that adult farmers lack access to quality, practical education on solar pumping systems and their agribusiness potential. The opportunity lies in the relatively rapid and low-cost means by which this gap can be addressed through targeted, participatory adult learning interventions delivered at the community level.

4.3 Effective Adult Learning Models for Solar Technology Adoption

Several pedagogical models have demonstrated effectiveness in promoting technology adoption among adult farmers. Farmer Field Schools (FFS), popularized by the Food and Agriculture Organization (FAO), bring small groups of 20–25 farmers together over a cropping season for experiential, discovery-based learning [FAO, 2021]. FFS adapted for solar irrigation have been implemented in Ghana, Tanzania, and Bangladesh with significant positive outcomes, including higher adoption rates, improved system management, and reduced failure rates due to improper use.

Community-based learning, where established solar irrigation adopters serve as resource persons and demonstration sites for neighboring farmers, leverages the social trust and practical credibility that extension-based education often lacks. This model is particularly effective in Nigeria's communalistic rural societies, where knowledge shared by a trusted peer carries more weight than formal instruction from an outsider.

Digital and radio-based extension, now expanding across rural Nigeria through platforms such as the Babban Gona digital advisory service and community radio stations, provides scalable, low-cost channels for solar irrigation education. Short-duration radio broadcasts in Hausa, Yoruba, Igbo, and other local languages that explain solar pump operation, maintenance, and financial management can reach millions of adult learners who may never attend a formal training program.

4.4 Barriers to Adoption Among Adult Learners

Despite the compelling advantages of solar pumping, several barriers impede its adoption among adult learners. Financial barriers are the most commonly cited. The high initial cost of solar pumping systems places them beyond the reach of most smallholders relying on personal savings or informal credit. Access to formal financial products — bank loans, microfinance, equipment leasing — remains limited in rural areas, particularly for unbanked farmers lacking collateral or credit histories [Aliyu et al., 2021].

Technical barriers are also significant. Adult learners with limited formal education may perceive solar technology as complex, intimidating, or prone to failure if mishandled. Concerns about system durability, theft, and after-sales service — particularly in remote areas far from solar technicians — create additional deterrents. The absence of a robust network of certified solar pump technicians in rural Nigeria means that when systems break down, repairs may be delayed for weeks or months, discouraging adoption.

Social and cultural barriers exist as well. In some communities, technology adoption is associated with risk-taking that conflicts with traditional farming norms. Gender dynamics further complicate adoption: women, who are significant actors in smallholder farming and food processing, may face greater barriers in accessing finance, training, and decision-making authority needed to invest in solar pumping systems.

V. CREATING AN ENABLING ENVIRONMENT: POLICY AND INSTITUTIONAL DIMENSIONS

5.1 Government Policy and Incentive Frameworks

The role of government policy in accelerating solar pump adoption cannot be overstated. In countries where solar irrigation has achieved significant scale — India, Bangladesh, Kenya, and Morocco — targeted policy interventions have been instrumental. These include subsidies on solar PV components, import duty waivers on solar equipment, dedicated rural solar irrigation programs, and integration of solar irrigation into national food security strategies.

Nigeria's National Renewable Energy and Energy Efficiency Policy (NREEEP) and the Renewable Energy Master Plan (REMP) provide a policy framework for renewable energy expansion. However, their agricultural dimensions — particularly concerning solar irrigation — remain underdeveloped. The Rural Electrification Agency's (REA) Energizing Agriculture Programme represents a positive step, but its scale remains limited relative to the national need [REA, 2023].

Policy recommendations drawn from the literature and field evidence include: (1) zero-rating or reducing import duties on solar pumping components; (2) establishing a dedicated Solar Irrigation Revolving Fund accessible through microfinance institutions; (3) incorporating solar irrigation into the National Agricultural Loan Scheme; and (4) mandating solar pumping content in all State ADP extension training curricula [World Bank, 2021; UNDP, 2022].

5.2 The Role of Microfinance and Rural Finance Institutions

Access to finance is the single most critical enabling factor for solar pump adoption among smallholder adult learners. Microfinance institutions (MFIs) and cooperative savings groups (thrift societies and osusu clubs) are often the most accessible and trusted financial intermediaries for rural farmers. Innovative financial products designed specifically for solar irrigation — such as asset-backed loans, pay-as-you-go (PAYGO) solar leasing, and group guarantee schemes — have proven effective in lowering the financial barrier to adoption in other African contexts [IFC, 2022].

The PAYGO model, in which farmers pay for their solar system in small, regular instalments tied to income cycles (weekly or monthly), has been particularly successful in Kenya and Tanzania for solar home systems and is now being extended to solar pumps. Several Nigerian fintech companies and development organizations are piloting PAYGO solar pump schemes in Niger, Kano, and Ogun States. Early results indicate strong farmer interest and manageable default rates when loan repayment terms are aligned with harvest income flows [SunCulture, 2022].

5.3 Private Sector and NGO Engagement

The private sector and non-governmental organizations have critical complementary roles in expanding solar irrigation access for adult learners. Solar equipment suppliers and distributors can expand rural reach through trained dealer networks and agent-based sales models. NGOs and international development organizations can finance demonstration projects, provide capacity building for extension agents, and conduct impact evaluations that build the evidence base for scaling.

Partnerships between solar companies, financial institutions, and adult education providers — facilitated by government or development agencies — offer a particularly powerful model. Such partnerships can bundle technical training, financial products, and equipment supply into comprehensive support packages for adult learner farmer groups. The example of the SunCulture solar irrigation initiative in Kenya, which combines PAYGO financing, agronomic advisory services, and after-sales technical support, offers a replicable model for Nigeria [SunCulture, 2022].

VI. ENVIRONMENTAL AND SOCIAL SUSTAINABILITY OF SOLAR IRRIGATION

6.1 Environmental Benefits and Sustainability Considerations

From an environmental perspective, the transition from diesel to solar-powered irrigation represents a significant improvement in the ecological footprint of smallholder agriculture. The near-zero operational carbon emissions of solar pumping systems contribute directly to climate change mitigation goals. Across Nigeria's agricultural sector, widespread adoption of solar irrigation could reduce diesel combustion by hundreds of millions of litres annually, preventing millions of tonnes of CO_2-equivalent emissions.

However, sustainable solar irrigation also requires responsible groundwater management. The ease and low cost of pumping with solar systems can, paradoxically, encourage over-extraction of groundwater resources if not accompanied by appropriate water governance frameworks. Hydrogeological surveys, community-based water management agreements, and crop water management training are essential complements to solar pump deployment to prevent groundwater depletion, particularly in already water-stressed regions [Giordano et al., 2019].

6.2 Gender, Youth, and Social Inclusion

Sustainable and inclusive agribusiness development requires that the benefits of solar irrigation reach women and young people, who are disproportionately represented among smallholder farmers but often disadvantaged in accessing new technologies. Targeted adult education programs that explicitly address gender and youth inclusion — through women-only training groups, female extension officers, and youth agricultural entrepreneur schemes — can help ensure that the productivity and income gains from solar irrigation are broadly shared.

Evidence from West Africa suggests that when women farmers gain control of solar-irrigated gardens, the income generated is more likely to be invested in children's education, household nutrition, and health care compared to income managed by male household heads [Ogunrinde et al., 2020]. This has multiplier effects on rural household welfare and community development, amplifying the broader social value of solar irrigation adoption.

VII. DISCUSSION

The foregoing analysis demonstrates that solar-powered pumping machines represent a highly promising technology for transforming dry-season agribusiness in Nigeria and comparable contexts. Their economic, environmental, and social advantages over diesel alternatives are well evidenced. The critical constraint is not technological — the systems are mature, proven, and commercially available — but rather an interplay of financial, educational, institutional, and policy barriers that impede widespread adoption among the adult learner farmer population.

Adult education emerges as a pivotal variable in the adoption process. Farmers who receive well-designed, participatory, practical training on solar irrigation systems are significantly more likely to adopt them, manage them correctly, and integrate them productively into their agribusiness operations. Educational interventions that align with adult learning principles — relevance, practical application, peer learning, and self-direction — consistently outperform didactic, classroom-based approaches in driving technology adoption outcomes [Knowles et al., 2015; Mezirow, 1997].

The policy environment plays an equally enabling or constraining role. Countries that have invested in deliberate, well-resourced solar irrigation programs — deploying the full range of policy tools from import duty waivers to dedicated financing to extension system reform — have achieved significantly higher rates of adoption than those relying on market forces alone. Nigeria's current policy landscape, while improving, falls short of the coherent, multi-pronged support framework that the available evidence suggests is required [World Bank, 2021; UNDP, 2022].

The integration of agribusiness education into solar irrigation programs is a dimension that deserves greater attention. It is insufficient to teach farmers how to operate solar pumps; they must also develop the business skills — financial planning, market analysis, cost accounting, value chain integration — that allow them to translate improved production into improved business outcomes. A holistic adult education approach that combines technical, agronomic, and agribusiness competencies is the model most likely to deliver transformative impact.

VIII. CONCLUSION AND RECOMMENDATIONS

This journal article has examined the adoption of solar-powered pumping machines for dry-season irrigation and its implications for agribusiness among adult learners. The evidence is unambiguous: solar irrigation is a technically viable, economically advantageous, and environmentally sound solution to the perennial challenge of dry-season water scarcity. Its potential to transform smallholder agribusiness — enabling year-round production, income diversification, and market competitiveness — is substantial and supported by robust empirical evidence from Nigeria and comparable contexts.

Adult learners, as the primary agents of agricultural transformation in rural Nigeria, must be at the center of solar irrigation uptake strategies. Achieving meaningful adoption at scale requires an enabling ecosystem comprising accessible financing, quality adult education, supportive policy, responsive extension systems, and inclusive social design. The recommendations arising from this analysis are addressed to a range of stakeholders:

For Government and Policymakers:

1) Develop a dedicated National Solar Irrigation Programme with dedicated budgetary allocation under the Federal Ministry of Agriculture.
2) Eliminate or significantly reduce import duties on solar pumping components to lower equipment costs.
3) Mandate solar irrigation modules in all State Agricultural Development Programme (ADP) curricula and extension agent training programmes.
4) Establish a dedicated Solar Irrigation Revolving Fund accessible through microfinance institutions and rural banks.
5) Incorporate solar irrigation into the National Agricultural Loan Scheme and other agricultural credit facilities.
6) Establish monitoring and evaluation frameworks to track solar irrigation adoption rates and impacts.

For Adult Education Institutions and Extension Services:

1) Develop and deploy context-specific, andragogically designed training modules combining solar technology, water management, and agribusiness skills.
2) Establish Farmer Field Schools and solar demonstration farms in each Local Government Area as experiential learning hubs.
3) Develop gender-sensitive training approaches to ensure equitable participation and benefit-sharing among women farmers.
4) Leverage digital and radio-based platforms to scale solar irrigation education to remote and underserved communities.
5) Integrate solar irrigation content into all agricultural extension training curricula.

For Financial Institutions:

1) Develop PAYGO and group guarantee solar pump financing products tailored to the income cycles of smallholder farmers.
2) Partner with State ADPs, farmer cooperatives, and solar suppliers to bundle financing with training and after-sales support.
3) Establish partnerships with fintech companies to expand access to solar irrigation financing in rural areas.

For Future Research:

1) Conduct longitudinal studies on the long-term economic and social impacts of solar irrigation adoption.
2) Investigate the effectiveness of different adult learning models for solar technology adoption.
3) Assess the groundwater sustainability implications of large-scale solar irrigation deployment.
4) Evaluate the effectiveness of PAYGO and other innovative financing models in the Nigerian context.

In conclusion, the harnessing of solar energy for pumping machines during dry seasons is not merely a technical intervention — it is a development strategy with far-reaching implications for agribusiness growth, rural income, food security, and environmental sustainability. When appropriately embedded in adult education frameworks and supported by enabling policy and finance, solar irrigation can be a cornerstone of Nigeria's agricultural transformation agenda.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

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