

Enhancing Reservoir Benefits through Floating Photovoltaic Development: A Case Study of Sutami Reservoir, Indonesia

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Abstract: Reservoirs that already support hydropower and water supply are increasingly viewed as sites for floating photovoltaic (FPV) development, a pairing that speaks directly to SDG 7 (Affordable and Clean Energy) and SDG 6 (Clean Water and Sanitation). Taking Sutami Reservoir in East Java as a case, this study examines an FPV layout occupying 5% of the reservoir's normal water surface area (602.499,80 m²), with attention to electricity yield, evaporation-related water savings, and financial viability. Energy output was estimated from irradiance and module-efficiency parameters, evaporation savings were derived from the change in exposed surface area, and feasibility was judged through four standard indicators: Net Present Value (NPV), Benefit-Cost ratio (B/C), Internal Rate of Return (IRR), and Payback Period (PP). At an installed capacity 100 MWp, the system is projected to generate 175.80 GWh annually – about 23,89% of the existing hydropower plant's output – while conserving roughly 2,48 million m³ of water per year, a 54,61% gain in raw-water benefit. The economic analysis is less clear-cut: NPV comes to Rp 26,03 billion and B/C reaches 1,01, but IRR sits at only 7,1% and payback stretches to 23,30 years against a 30-year assumed project life – leaving roughly seven years of net benefit at the end, a narrower window than the headline numbers suggest. Taken together, the results point to real technical benefits from combining energy generation with water conservation at Sutami Reservoir, though the thin economic margin warrants a closer sensitivity analysis before the project moves toward implementation.

Keywords: Evaporation reduction; Floating photovoltaic; Renewable energy; Reservoir operation; Water conservation

Introduction

Rising electricity demand and mounting concern over climate change have pushed the global energy transition forward more quickly than many anticipated a decade ago. Solar power sits at the center of this shift: its cost has fallen steadily, resource availability is abundant, and operational environmental impacts remain minimal relative to fossil alternatives (Osman et al., 2023). Floating photovoltaics (FPV) has grown rapidly within that shift, increasingly viewed as a technology that can ease land-use pressure while adding renewable capacity (Ramanan et al., 2024; Oeishee & Rahman, 2026). Indonesia has responded with ambitious renewable energy targets aimed at both energy security

and emissions reduction, which in turn has raised the stakes for developing solar technologies suited to local conditions.

One such condition is land scarcity. Ground-mounted photovoltaic systems compete directly with agriculture, settlement, and conservation land, a constraint that floating photovoltaic (FPV) technology sidesteps by placing modules on reservoirs, lakes, and ponds instead (Spencer et al., 2019). Whether this actually translates into a cost advantage depends heavily on where the system is built: Patil et al. (2017) describe comparatively flexible siting rules for structures on non-recreational water bodies, but that observation does not carry over cleanly to Indonesia, where reservoir development is closely regulated – Ministry of Public

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Works and Housing Regulation No. 6/2020, for instance, caps FPV coverage at 5% of a reservoir's surface area. A further, more consistent advantage of water siting is thermal: the cooling effect of the water surface tends to raise module efficiency relative to land-based installations (Sukarso & Kim, 2020).

FPV's appeal is not limited to energy. Covering part of a reservoir surface blocks direct solar radiation from reaching the water below, which in turn slows evaporation—a genuinely useful property in a tropical country where evaporative losses eat into reservoir storage year-round (Abdelal, 2021; Kassem et al., 2024). At the global scale, FPV deployment on reservoirs has been estimated to conserve well over 100 km³ of water annually alongside its energy contribution (Jin et al., 2023), and pairing FPV specifically with existing hydropower reservoirs has been shown to compound these benefits by reducing evaporation while adding generation capacity to infrastructure that is already in place (Kakoulaki et al., 2023; Gonzalez Sanchez et al., 2021). Indonesia is reasonably well positioned to exploit this: solar irradiation is favorable, reservoirs are numerous, and the Cirata Floating Solar Power Plant has already shown that large-scale FPV is technically achievable here, a potential now being explored on other Indonesian sites as well (Esparza et al., 2024). Many reservoirs, however, remain untouched by this potential. Sutami Reservoir in East Java is a case in point: it has a large surface area, an existing hydropower plant to complement, and a central role in regional water management, yet it continues to lose water to evaporation like any other tropical multipurpose reservoir.

Much of the existing FPV literature, including several Indonesian studies that followed Cirata's example, tends to isolate one dimension of performance at a time—energy yield, economic return, or environmental effect—rather than treating them together. Studies in India, for instance, have quantified FPV's evaporation-reduction and carbon-emission benefits for individual reservoirs (Ravichandran et al., 2022), while others have focused specifically on the economics of pairing FPV with existing hydroelectric plants (Singh et al., 2022) or on the global technical potential of such hybrid systems (Lee et al., 2020). What is harder to find is a study that ties energy generation, evaporation-driven reservoir routing, and economic feasibility into a single framework for a reservoir with pronounced seasonal water-level swings. That gap is the specific entry point for this paper: rather than treating the FPV footprint as fixed against a static reservoir, the analysis here links a reservoir operation simulation to the energy and economic assessment so that the effect of fluctuating water levels on both the evaporation benefit and the reliability of the footprint assumption can be

seen explicitly—a link that prior Indonesian FPV studies have rarely made.

Against this backdrop, the present study evaluates FPV implementation at Sutami Reservoir along four fronts—energy generation, evaporation reduction, reservoir performance, and economic feasibility—within one evaluation framework. The intent is not merely descriptive: bringing these strands together is meant to inform how FPV development strategy in Indonesia might account for reservoirs where water levels do not stay put, and more broadly to support the country's parallel goals of clean energy and sound water resource management.

Method

Research Design

Evaluating what an FPV system would actually mean for Sutami Reservoir is not something that can be settled from a single dataset or a single calculation; it requires piecing together several strands of evidence that, on their own, only tell part of the story. This study leans on secondary data drawn from a handful of sources: reservoir operation records and the capacity curve maintained by the reservoir operator, topographic and bathymetric surveys that describe the basin's shape, solar irradiation and evaporation figures for the surrounding area, production logs from the existing hydropower plant, and the technical specifications published for the photovoltaic module under consideration. None of these datasets was collected with this particular question in mind, so part of the analytical work lies in bringing them into a common frame before any calculation can proceed.

Rather than treating the assessment as one undifferentiated exercise, the analysis follows the sequence set out in Figure 1, moving through data collection, FPV design analysis, and a chain of calculations that carries the technical findings through to the economic bottom line. It starts with data collection, since every later step depends on having a consistent, verified picture of the reservoir to work from. FPV design analysis follows, fixing the layout and footprint within the physical and regulatory constraints that apply at the site. From there the calculations turn technical: first the decrease in exposed water surface area that the FPV footprint brings about, then the evaporation reduction that follows from that smaller surface, and then a comparison of the reservoir's operating pattern before and after FPV installation, since the water conserved through evaporation reduction does not sit still—it has to be traced as it moves through the reservoir's storage and release cycle over time. Only once that comparison is in hand does the analysis calculate the additional benefits the reservoir gains—in

energy and in water—before finally turning to economic feasibility, weighing what the system would cost against what it would return over its operating life. Each stage in this chain draws directly on the one before it, so that the economic conclusions at the end rest on technical assumptions that have already been made explicit rather than being bolted on separately.

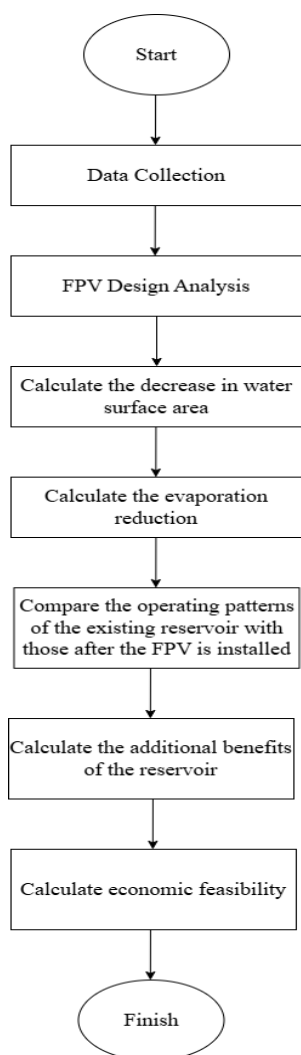


Figure 1. Flowchart of the study

Study Area and Data Collection

Sutami Reservoir, in East Java, serves multiple functions at once—hydropower generation, water regulation, flood control, and environmental conservation—and its Normal Water Level (NWL) surface area of 12.049.996,09 m² leaves considerable room for FPV development. Perum Jasa Tirta I supplied the core secondary data: reservoir operation records, the capacity curve, topographic surveys, and evaporation figures, rounded out with solar irradiation data, module specifications, and the economic parameters needed for the feasibility analysis. The photovoltaic module

modeled throughout is the Jinko Solar Tiger Neo 72HL4-(V).

Floating Photovoltaic Design

Ministry of Public Works and Housing Regulation No. 6/2020 caps FPV coverage at 5% of a reservoir's NWL surface area, and the layout here was sized accordingly. Siting also had to satisfy several operational and safety margins: at least 500 m from the dam body, 100 m from intake structures, 3 m of water depth above the Minimum Operating Level, and 50 m of spacing between FPV islands. The resulting footprint became the basis for estimating installed capacity and generation potential in the sections that follow.

Energy Production Analysis

Generation potential follows from three inputs—available photovoltaic area, solar irradiation, and system efficiency—combined in the manner used by Nainggolan et al. (2024) for daily electricity output:

$$Ep = APv \times Gav \times TCF \times \eta_{PV} \times \eta_{inv} \times \eta_{out} \quad (1)$$

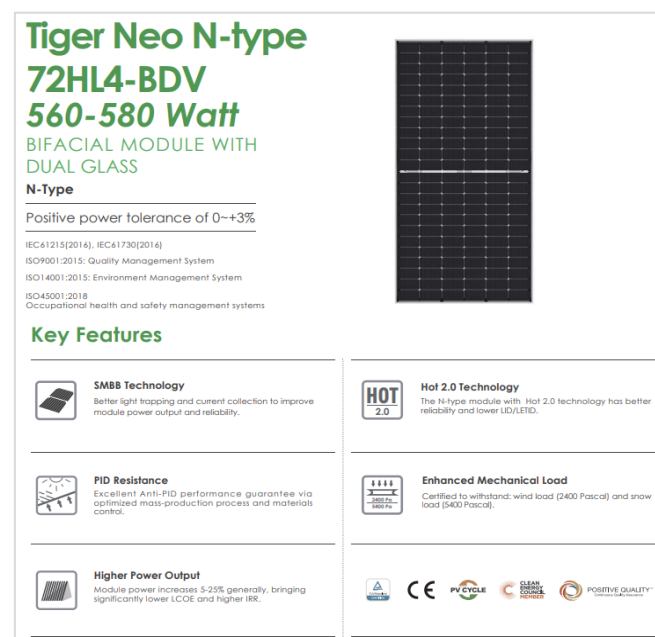


Figure 2. Jinko solar tiger neo 72HL4-(V) PV module specifications

Here, APv is the photovoltaic module area (m²), Gav the average solar irradiation (kWh/m²/day), TCF the temperature correction factor, η_{PV} the photovoltaic module efficiency, η_{inv} the inverter efficiency, and η_{out} the combined efficiency of the remaining system components. Ambient temperature at Sutami Reservoir, taken from the Global Solar Atlas, averages 26,6°C, or 0,4°C above the 25°C standard test condition for the Jinko Solar Tiger Neo 72HL4-(V) module used in this design. Applying the module's temperature coefficient

of $-0,29\%/^{\circ}\text{C}$ to that $0,4^{\circ}\text{C}$ difference gives an efficiency loss of 0.116% ($\text{TCF} = 0.998$), leaving an effective panel efficiency η_{PV} of 22.84% per the module datasheet.

Inverter efficiency η_{inv} was taken as 98.8% , and the efficiency of other balance-of-system components η_{out} as 85% .

Table 1. Technical Data of Jinko Solar Tiger Neo 72HL4-(V) PV Module

Mechanical Characteristics	Description
Cell Type	N type Mono-crystalline
No. of Cells	144 (2×72)
Dimensions	2278 × 1134 × 30 mm (89.69 × 44.65 × 1.18 inch)
Weight	32 kg (70.55 lbs)
Front Glass	2.0 mm, Anti-Reflection Coating
Back Glass	2.0 mm, Heat Strengthened Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP68 Rated
Output Cables	TUV 1 × 4.0 mm ² (+): 400 mm, (-): 200 mm or Customized Length

Evaporation Reduction and Reservoir Operation Analysis

Evaporation rates were not derived analytically but taken as secondary data from BMKG (the Indonesian Agency for Meteorology, Climatology, and Geophysics)—an alternative to the direct evaporation-modeling approaches (e.g., Penman-Monteith) used in comparable FPV evaporation studies elsewhere (Abdelal, 2021; Kassem et al., 2024). Applying these observed rates to the reservoir's exposed water surface area before and after FPV installation—on the reasoning that a covered surface receives less direct solar radiation and therefore evaporates more slowly—gives a first estimate of evaporation savings. That conserved volume was then folded back into the reservoir's storage account and traced through the elevation–area–storage relationship, using a monthly water-balance (reservoir routing) simulation that also accounts for turbine and spillway outflow alongside the ordinary inflow.

Economic Feasibility Analysis

Four standard indicators—NPV, B/C, IRR, and PP—carried the financial side of the evaluation, drawing on investment costs, operation and maintenance costs, electricity revenue, and the value of water conserved through evaporation reduction, following the approach set out by Magableh et al. (2024). The analysis used a discount rate of 6% , the applicable benchmark rate for 2024, over an assumed project life of 30 years. Electricity revenue followed the two-tier tariff structure set out in Presidential Regulation of the Republic of Indonesia No. 112 of 2022 concerning the Acceleration of Renewable Energy Development for Electricity Supply, under which the tariff applied in years 1–10 of operation differs from that applied in years 11–30; all benefit values were converted to Rupiah using an assumed exchange rate of Rp 15.731 per USD. The conserved water was valued at Rp 133/m³, the lowest raw-water tariff published by Perum Jasa Tirta I. A project counted as feasible only if it returned a positive net financial result against the criteria set for each indicator.

Result and Discussion

Design and Location of FPV

Applying the 5% coverage limit to the NWL surface area yields an FPV footprint of $602.499,80 \text{ m}^2$, sited to keep at least 500 m of clearance from the dam body, 100 m from intake structures, and 3 m of water depth above the Minimum Operating Level.

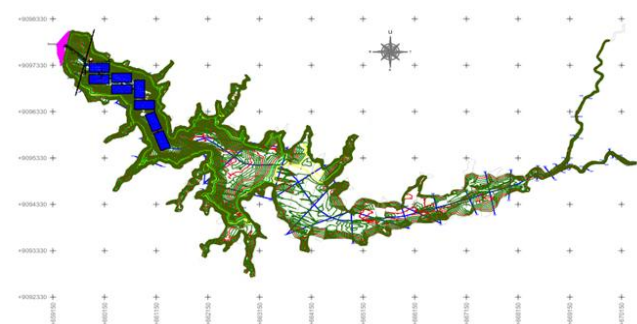


Figure 3. Sutami reservoir floating solar power plant placement plan

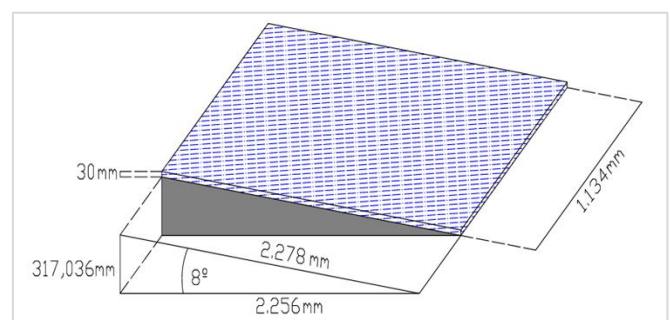


Figure 4. 8° tilt solar module design

The module mounting structure was also tilted rather than laid flat, a choice that matters more for energy yield than it might first appear. Sutami Reservoir sits a few degrees south of the equator, and for sites in this position the sun tracks slightly to the north of zenith across most of the year; tilting the array toward the north lets the module face more directly into that average sun

position instead of receiving light at a steeper, less efficient angle. Rather than assume a tilt angle, this study took the value from the Global Solar Atlas for the Sutami site, which returned an optimum tilt of 8° toward north for maximizing annual irradiation capture at this latitude. Figure 4 shows how that tilt was translated into the physical mounting structure.

Reduction of Reservoir Surface Area due to Floating Photovoltaic Deployment

Water level conditions	Elevation (m)	Existing reservoir area (m ²)	Reservoir area with FPV (m ²)	Area difference (m ²)	Percentage of reservoir water surface area decrease (%)
NWL	272	12,049,996,09	11,447,496,29	602,499,80	5
MOL upper limit	260	4,317,265,70	3,714,765,90	602,499,80	13,96
MOL lower limit	246	2,002,924,56	1,400,424,76	602,499,80	30,08

Figure 5. Percentage reduction of sutami reservoir water surface area

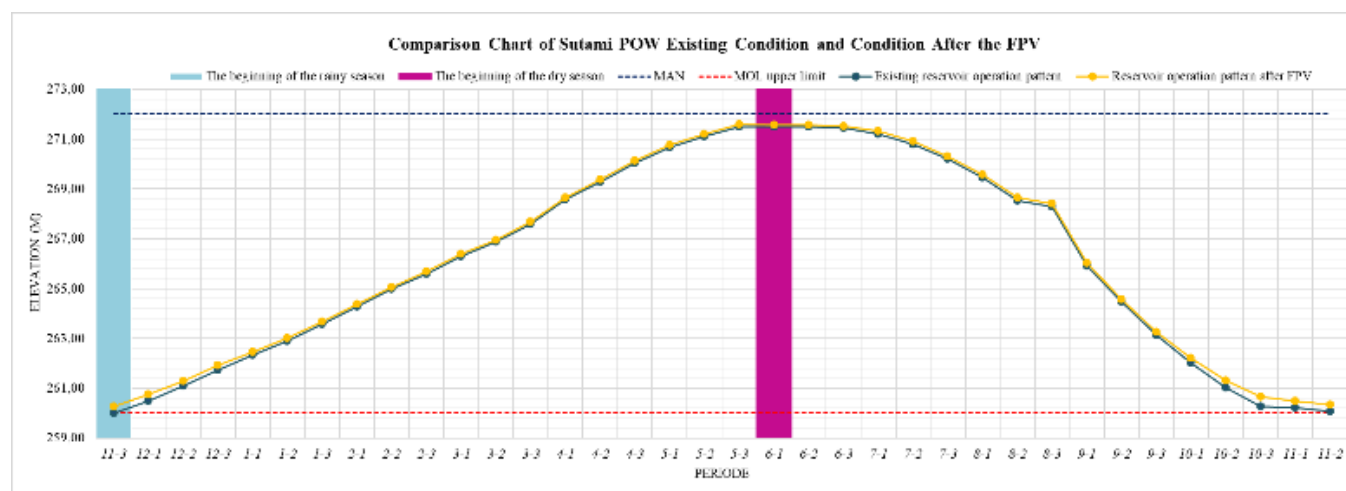


Figure 6. Visualization of comparison of elevation of sutami reservoir operation pattern

Additional Reservoir Storage Volume

Roughly 2.479.889,20 m³ of water a year stays in Sutami Reservoir under FPV that would otherwise have evaporated, and that volume is not a one-off gain—it accumulates within storage and adds directly to what the reservoir can draw on. In that sense, FPV's contribution here is not just electricity but a modest, ongoing improvement in how efficiently the reservoir holds onto the water it already has.

Increase in Reservoir Benefits

With APV = 602.499,80 m² and Gav = 5,220 kWh/m²/day, daily generation works out to 602.046,34 kWh/day (602,05 MWh/day); scaling by 365 days and an annual generation factor of 80% gives 175.797.531,28 kWh/year, or roughly 175,80 GWh/year. That figure was then set against the existing hydropower plant's annual production to gauge the additional energy benefit FPV would bring. Between the two sides of the ledger, FPV adds 175.797.531,28 kWh of electricity a year—about 23,89% on top of what the existing

Changes in Reservoir Operation Pattern

Running the monthly water-balance simulation with and without FPV in place, Figure 6 shows the post-FPV water level tracking consistently above the existing operation curve—the natural result of evaporation savings accumulating month over month rather than a single dramatic jump. That gap widens when storage is already low, which suggests the retained water matters most exactly when the reservoir can least afford to lose it, adding a measure of resilience through dry periods. No single month shows a large elevation gain, but the cumulative effect across a full year is large enough to register as a genuine improvement in reservoir performance.

hydropower plant already produces—and conserves 2.479.889,20 m³ of water annually, a 54,61% lift in raw-water benefit relative to current conditions. Neither gain comes at the expense of the other: the reservoir keeps its primary functions intact while picking up energy and water benefits side by side, which is arguably the strongest technical case for FPV at a site like Sutami.

Economic Feasibility Analysis

Weighing capital investment, operation and maintenance costs, electricity revenue, and the added value of conserved water against one another produces an NPV of Rp 26.028.319.363,12, a B/C ratio of 1,01, an IRR of 7,1%, and a payback period of 23,30 years.

Each of these numbers looks better in isolation than it does alongside the others. A B/C ratio of 1,01 means benefits clear costs by roughly one percent—not much of a buffer against a cost overrun, a tariff cut, or panels that underperform their rated efficiency over time. Set against the 30-year project life assumed in this analysis, a 23,30-year payback leaves only about seven years,

roughly a fifth of the system's working life, in which the project actually earns net benefit—a real margin, but not the comfortable one the phrase 'financially feasible' tends to imply. IRR tells a similar story: at 7,1% against a 6% discount rate, the project clears feasibility, but by only about one percentage point, which is a thin buffer given how sensitive IRR estimates are to cost and revenue assumptions over a 30-year horizon. Even the headline NPV figure is less reassuring once set against the B/C ratio—a positive NPV of this size next to a B/C barely above 1,0 implies total project costs likely running into the trillions of rupiah, against which Rp 26 billion in net benefit is a slim return indeed.

What is harder to explain away is the gap between the technical and financial pictures: energy output up nearly 24%, raw-water benefit up more than half, yet the money barely works out. The most plausible explanation is that floating infrastructure—floats, mooring, anchoring, marine-grade cabling—simply costs more than a ground-mounted system to build, or that the electricity tariff and raw-water price fed into the model are conservative, or some combination of the two. This is consistent with sensitivity studies elsewhere showing that capital expenditure and electricity price are typically the two variables with the largest influence on FPV's NPV and IRR (Micheli et al., 2024), and with feasibility assessments of hybrid hydro-FPV projects that likewise report thin margins once realistic capital costs are applied (Singh et al., 2022). Sorting out which factor dominates here would call for a sensitivity analysis that varies capital cost, tariff, discount rate, and raw-water price to see what combination would actually make this project comfortably, rather than marginally, worthwhile.

Conclusion

At Sutami Reservoir, FPV deployment stands to add about 175,80 GWh of electricity a year—23,89% on top of the existing hydropower plant—while conserving roughly 2,48 million m³ of water annually through reduced evaporation, a 54,61% gain in raw-water availability. On the technical side, then, FPV clearly earns its keep, improving both the energy and water performance of the reservoir without disturbing what it was already built to do. The economics tell a less settled story: a B/C ratio of 1.01, an IRR of 7,1%, and a payback period of 23,30 years amount to a project that clears its feasibility hurdles by very little, leaving scant room for cost overruns or tariff shifts. That gap between solid technical gains and marginal financial ones is really the central finding here, and it is where any decision to move toward implementation should focus its scrutiny—on capital costs, financing terms, and the

revenue assumptions driving these numbers. Three directions seem worth pursuing next. First, a sensitivity analysis across capital cost, electricity tariff, discount rate, and raw-water price would clarify what would need to change for this project to clear feasibility more comfortably rather than marginally. Second, the fixed-footprint assumption used here deserves testing against an explicit model of mooring-system behavior under fluctuating water levels, since that assumption underlies both the evaporation estimate and the safety picture near MOL. Third, field measurement or a Penman-Monteith-based approach would put the evaporation-reduction estimates on firmer empirical ground than the area-based method used in this study. Together, these steps would give decision-makers a sturdier basis for weighing FPV development at Sutami Reservoir—and at other Indonesian multipurpose reservoirs facing the same trade-offs.

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Author Contributions

Conceptualization, I.I.D.A.A.P., P.T.J., and A.P.H.; methodology, I.I.D.A.A.P.; validation, I.I.D.A.A.P., P.T.J., and A.P.H.; formal analysis, I.I.D.A.A.P.; investigation, I.I.D.A.A.P.; resources, I.I.D.A.A.P.; data curation, I.I.D.A.A.P.; writing—original draft preparation, I.I.D.A.A.P.; writing—review and editing, P.T.J. and A.P.H.; visualization, I.I.D.A.A.P.; supervision, P.T.J. and A.P.H.; project administration, I.I.D.A.A.P.; funding acquisition, I.I.D.A.A.P. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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