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Mini Review

Abolhassan Mohammadi Fathabad, Christopher B. Yazzie, Jianqiang Cheng
and Robert G. Arnold*

Optimization of solar-driven systems for off-grid water nanofiltration and electrification

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Abstract: The work described is motivated by an inability to extend central infrastructure for power and water to low-population-density areas of the Navajo Nation and elsewhere. It is estimated that 35% of the Navajo population haul water for household use, frequently from unregulated sources of poor initial quality. The proposed household-scale, solar-driven nanofiltration (NF) system designs are economically optimized to satisfy point-of-use water purification objectives. The systems also provide electrical energy for a degree of nighttime household illumination. Results support rational design of multiple-component purification systems consisting of solar panels, a high-pressure pump, NF membranes, battery storage and an electrical control unit subject to constraints on daily water treatment and excess energy generation. The results presented are conditional (based on initial water quality, membrane characteristics and geography) but can be adapted to satisfy alternative treatment objectives in alternate geographic, etc. settings. The unit costs of water and energy from an optimized system that provides 100 gpd (1 gallon is 3.78 L) and 2 kWh/day of excess electrical energy are estimated at \$0.16 per 100 gallons of water treated and \$0.26 per kWh of nighttime electrical energy delivered. Methods can be used to inform dispersed infrastructure design subject to alternate constraint sets in similarly remote areas.

Keywords: membrane filtration; nanofiltration; off-grid water treatment; solar energy; system optimization.

Introduction

The Navajo Nation, parts of which lie in Arizona, New Mexico and Utah was the study site for method development and application. Due to low population density (<13/miles² on average) it is estimated that 35% of Navajo residences are not connected to central infrastructure for water or power delivery (1). Universal extension of central infrastructure is economically infeasible in areas of lowest population density. The problem is compounded by unavoidable reliance on ground water throughout much of the Navajo Nation. Although ground water is plentiful at depth, much of it is brackish in character [total dissolved solids (TDS) ≥ 2000 mg/L] (2) and/or contains contaminants, for example, arsenic and uranium, at concentrations that exceed U.S. maximum contaminant levels (MCLs) for drinking water (3). Thus, residents frequently rely on unregulated sources – most often springs or other near-surface, unconfined ground waters that are of nebulous initial quality (4, 5).

The Navajos are not the only Native Americans that would benefit from the development of small-scale, low-cost, off-grid water purification systems (6). The proposed resolution of such problems rests on the development of affordable point-of-use water treatment systems driven by renewable power. The problem occupies one corner of what has become the energy-water nexus (7). The technical solution must be capable of separating uranium, arsenic and a substantial fraction of the TDS from water without yielding a brine disposal problem. Solar-driven nanofiltration (NF) is proposed here (8, 9). System components include a solar array, a high-pressure pump, NF membranes, batteries and electrical controls.

Currently there are approximately 34,000 off-grid Navajo tribal members who can be candidates for residential power from photovoltaic systems. Photovoltaic power systems in remote locations are generally more cost affordable than running single-phase line extensions. Through the help of non-governmental organizations, the Navajo Tribal Utility Authority and small businesses,

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off-grid power has improved the lives of tribal residents starting in the late 1980s. The Navajo Nation is among the most researched rural populations that utilize the technology (10). Off-grid energy and water infrastructure projects can create jobs and improve life among tribal residents (11, 12). The results described here have value as both a stand-alone objective and as a technical demonstration.

System optimization, constrained to produce 100 gallons of water per day (1 gallon is 3.78 L) and 2 kWh of excess electrical energy for nighttime use, is pursued using a genetic algorithm (13, 14). The results illustrate the practical utility of off-grid infrastructure development in remote parts of the Navajo Nation, but can be applied with equal effect in similarly isolated communities under alternate geographic conditions with modestly different demands for water and power.

Modeling and optimization methods

The general approach to the problem follows – the objective was to minimize the present-value cost of a household-scale, solar-NF system consisting of (i) a solar array,

(ii) a high-pressure pump, (iii) an NF membrane and (iv) batteries (Figure 1) subject to constraints on daily water treatment and excess energy production/storage for nighttime use. Other system components, for example, water storage tanks, pipes, valves, flow meters, etc. were omitted from the objective function as independent of scale and therefore not subject to optimization. The hypothetical treatment system was arbitrarily constrained to provide 100 gpd of treated water and 2 kWh of excess energy for nighttime use.

Governing equations

Constitutive (operational) requirements imposed on the system included satisfaction of the continuity equation for water and an energy balance throughout a standard day of operation. Details are as follows:

The objective function for the optimization problem consisted of present value costs attributable to equipment items in the solar-NF system (Figure 1) that vary in size as a consequence of design or operating decisions. For convenience, equipment costs were sometimes represented as continuous functions of scale using available commercial data for guidance – for example, Figure 2. Cost function,

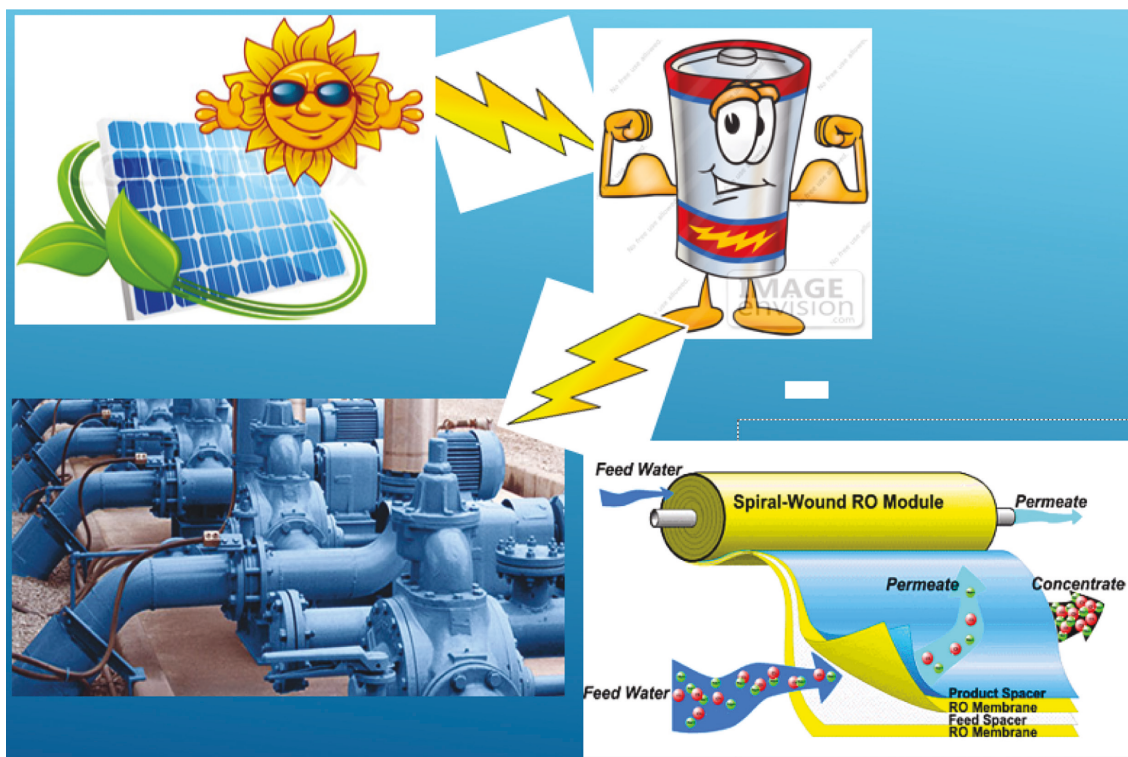


Figure 1: System components included in the cost optimization study – solar array, batteries, pump and NF membrane. Other system elements such as pipes and valves are omitted inasmuch as their cost contribution is essentially independent of component scale.

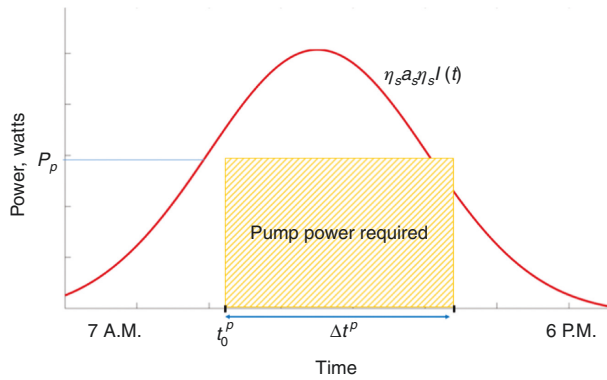


Figure 2: Bases of the energy balance.

Captured solar energy (red line) must exceed pump power requirements by nighttime power use (E). $I(t)$ was obtained by fitting the published irradiance level at 36°N (15).

parameter selection and optimized results for solar-NF system components are summarized (Table 1). Service lives for the solar array, pump and NF membranes/membrane canister were assumed to be 20 years. Expected battery life, however, was complicated by an inverse relationship between expected life and routine battery draw-down or depth of discharge (DoD) (the fraction of battery capacity that is expended each day to supply energy from storage). The battery DoD was thus the ratio of stored energy used each day to satisfy excess energy requirements to the total battery capacity (a decision variable that appears in the objective function). System constraints (daily water production and nighttime energy use) were problem parameters, as opposed to decision variables. A complete list of decision variables (those operating and design variables that were computationally selected to minimize the present value cost of the system) and system parameters is provided in Table 1.

Constitutive equations that result from continuity and the energy balance were satisfied at 1-h intervals throughout the “standard day” simulated. These balances are linked at the pump/membrane interface through the operating pressure and flow rate as follows:

The pump power requirement is proportional to the discharge rate and delivered pressure per:

$$P_p = \gamma_w \rho Q / \eta_p \quad (1)$$

where Q is the pump discharge rate $= Q_d / (24 / \Delta t^p)$, and γ_w is the specific weight of water. The rate of water purification or permeate flow during NF is given by:

$$Q_p = a_m A (\rho - \Delta \pi) \quad (2)$$

The recovery of feed water as permeate (unitless) during NF is defined as:

$$R = Q_p / Q \quad (3)$$

The energy used by the pump over time interval Δt (s) is $P_p \Delta t$ ($ft - lbf$), thus linking system energy use to water production. In general, recovery during NF is limited by the possibility of precipitation events in the concentrate, with consequent membrane scaling. Thus, selection of a target recovery will be site- or case-specific and determined by raw water quality. For these purposes, a value of 0.5 was arbitrarily selected as a representative. The sensitivity of capital and operational costs to system recovery is beyond the scope of the work described here.

In order to provide sufficient energy to operate the pump during its entire period of daily use and generate sufficient energy to satisfy nighttime use requirements, the photovoltaic energy produced must be at least as great as the pump energy demand plus the nighttime energy demand. That is:

$$\eta_s a_s n_s \int_0^{24} I(t) dt - \Delta t^p P_p - E \geq 0, \quad (4)$$

In order to track the energy status of the battery throughout the day (leading to determination of the DoD) it is necessary to satisfy an energy balance on the system for each hour of the day:

$$\eta_s a_s n_s \int_{t=t}^{t+1} I(t) dt - P_p^t - E^t + q^{t-1} - q^t = 0, \quad \forall t \in T, \quad (5)$$

where $P_p^t = \frac{P_p}{\Delta t^p}$ is hourly energy demand by the pump when in use, and $E^t = \frac{E}{\Delta t^e}$ is the hourly energy demand for the nighttime electrification when used.

This system energy balance is fairly easy to visualize (Figure 2). The difference between energy provided from the solar array and energy demand by the pump is stored temporarily in the battery bank or, when the batteries are fully charged, wasted as heat. If excess energy is to be provided from the system during nighttime hours, that energy (here 0 or 2 kWh) must be generated by the solar array in excess of pump demand during hours of daylight operation (Eq. 4). If there is to be 2 kWh of energy for nighttime use, the solar array must be large enough to both deliver energy to the pump for treatment of 100 gpd of water plus 2 kWh for battery storage and nighttime consumption. The

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Table 1: Summary of values for problem parameters (fixed) and decision variables (calculated) to minimize the present value cost of solar-NF system components.

Decision variable (units)		Cost function	Optimal values	
			Case (a)	Case (b)
n_s	No. of solar panels ()	$C_s = \$95/\text{panel}$	1	3
P_p	Pump power demand, Watts	$C_p = \$0.48/\text{Watts}$	138	161
a_m	Membrane surface area, m^2	$C_m = \$21.42/\text{m}^2 + \268	39	32
n_b	Number of batteries ()	C_b refer to Eq. 8	1	8
t_0^p	Starting time for water production (time of day)		10 A.M.	10 A.M.
Δt^p	Daily length of water production period, h		8.0	6.7
DoD	Depth of discharge of battery ()		0.06	0.21
L_{fail}	Life of Batteries, years		15.8	8.5
ρ	Pump pressure, ATM		2.24	2.72
q^t	State of the charge of the battery at time t, or fraction of battery capacity available ()			
Parameters (units)		Value selected		
Q_d	Minimum daily water production, gpd	100 (fixed, all simulations)		
R	Recovery rate during NF ()	0.5		
Q_p	Membrane permeate flow rate, ft^3/s	50		
E	Minimum nighttime energy use, kWh	0 or 2 [fixed for case (a) or case (b)]		
$I(t)$	Daily Solar irradiance, W/m^2	Figure 3; function of latitude; clear sky assumption		
η_p	Pump efficiency ()	0.35		
η_s	Solar panels efficiency ()	0.17		
a_p	Area of each solar panel, m^2	0.7		
A	Membrane-specific coefficient of permeation, $\text{L}/\text{s} \cdot \text{m}^2 \cdot \text{atm}$	0.0157		
$\Delta \pi$	Difference in osmotic pressure across the membrane, atm	0.81		
T	Planning increments in a day	Hourly; $T = 24$		
S_b	Cost of a 12 V, 100 A.h. battery ()	\$160		

See text for problem statement. Case (a) is based on purification of 100 gpd without generation of excess power; case (b) 100 gpd in purification and 2 Kwh excess energy generated for nighttime use.

batteries must be large enough to provide 2 kWh of energy for nighttime use without unwarranted (sub-optimal) drawdown (DoD) from battery capacity.

The trade-offs that exist in sizing the solar array, pump, membrane and battery bank are apparent. That is, a large pump leads to a relatively small membrane surface area and/or short pump operational period. The solar array must satisfy energy requirements during a standard operational day. Battery storage must satisfy

nighttime energy demands and avoid interruption of system operation during the day.

Cost calculations

Cost functions (Figure 2) were developed for equipment components including pumps and solar arrays from manufacturers' data. Off-the-shelf components such as

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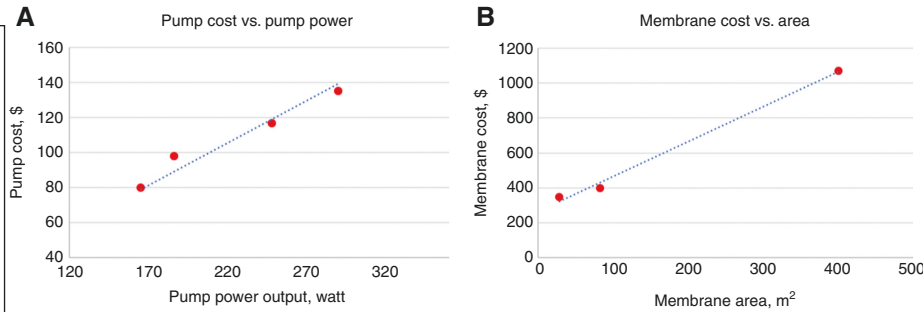


Figure 3: Continuous cost functions for the (A) pump cost as a function power rating, (B) NF membrane cost as a function of the area.

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membrane modules and batteries were given a single unit price (manufacturers' data) so that their unit cost was independent of scale.

The objective function represents total system cost over a 20-year system lifetime. Future costs are brought to present value using a discount operator $r = 0.05/\text{year}$.

The cost of the solar panels is equal to the unit cost of the solar panels ($\$C_s$) times the number of panels required. Pump-cost (C_p) and membrane-cost (C_m) relationships were developed using manufacturers' data and least squares regression analysis to fit a linear trend line to the data provided. All costs are in 2019 dollars.

The cost of batteries was determined as the present value of the batteries over a 20-year system lifetime. Battery lifetime was a function of the daily battery DoD, which governed the number of daily battery cycles to eventual failure (Eq. 6) (16) and an assumption that the system operates 365 days a year.

$$L_{\text{fail}} = \begin{cases} -48.3 * \text{DoD} + 18.5, & 0 \leq \text{DoD} < 0.3 \\ -11.3 * \text{DoD} + 8.3, & 0.3 \leq \text{DoD} < 0.5 \end{cases} \quad (6)$$

Which led to an annualized battery cost over their useful life cycle,

$$A = n_b S_b \frac{(1+r)^{L_{\text{fail}}} r}{(1+r)^{L_{\text{fail}}} - 1} \quad (7)$$

The present value of batteries over a 20-year period is then:

$$c_b = \frac{A}{r} - \frac{A}{r(1+r)^{20}} \quad (8)$$

making the objective function:

$$f(\mathbf{x}) = C_s n_s + C_m a_m + C_p P_p + C_b n_b \quad (9)$$

where $\mathbf{x}$ is the vector of the independent decision variables. The optimization problem was to minimize $f(\mathbf{x})$ subject to

constraints on daily water purification and generation of excess energy, while satisfying the continuity of energy balances.

Optimization methodology

The objective function was minimized using a genetic algorithm, a brute force method in which combinations of the independent decision variables that satisfy system operational constraints are compared in terms of their effect on the problem objective function (Eq. 9). There are many nonlinearities in the optimization model as configured – in both the objective function and constraints; this eliminated other optimization methods and led to the procedure selected.

There are five independent decision variables at the core of the proposed optimization model – the number of solar panels, area of the membrane, the time of day for starting the pump, the length of time that the pump is operated, and the number of batteries. Values selected for the decision variables, in combination, must satisfy system constraints (water and energy demands) as well as the continuity (water conservation) and conservation of energy equations. For combinations that satisfy constraints, system costs are calculated and compared to those of other feasible solutions until the minimum cost combination is identified. Procedures used to search among feasible solutions to find the minimum cost design are specific to each genetic algorithm. The search procedure used here was the Matlab® Global Optimization Toolbox's Genetic Algorithm (14, 17). A schematic representation of the search procedure follows (Figure 4).

The genetic algorithm selects a random population (set of values for decision variables) to initiate the procedure. It then searches for improved (lower cost) solutions, mimicking genetic operations such as crossover and mutation to alter the population in the search process. In this manner, the algorithm searches throughout the feasible

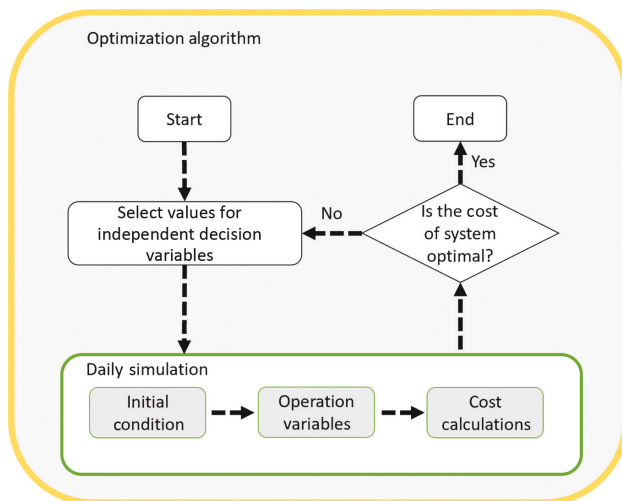


Figure 4: Summary of optimization procedure.

The genetic algorithm alters decision variables in order to find the minimum cost design.

solution region for the minimum cost population until one of the stopping criteria (e.g. failure to improve the solution over a specified number of generations) is met (14).

Results and discussion

Solar-NF system components were optimally sized to produce case (a) a minimum of 100 gpd (only) or case (b) both 100 gpd of purified water plus 2 kWh of excess energy for nighttime use. A number of operational conditions (starting time for water production, length of water production period and battery DoD) were likewise optimized. The results for the two cases are included in Table 1. System costs are broken down in Figure 5.

As the solar array, pump and membranes are assumed to last over the 20-year design period, their contributions to present value cost are equal to their capital cost. This is not true for the batteries, whose useful life is a function of DoD. In this application, expected battery life in the system designed for water purification alone was 15.8 years, so that battery replacement was expected only 1 time during the 20-year planning period. Batteries in the system designed for water purification and a degree of nighttime electrification had an expected life of only 8.5 years due to greater DoD.

The results highlight the relative importance of membrane cost, equal to 52% of the total present value cost when nighttime energy was not required. When the system was constrained to produce 2 kWh of excess energy for nighttime use, the system present value cost

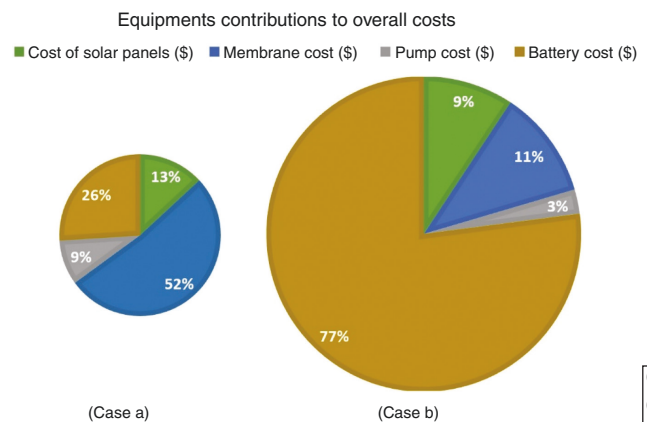


Figure 5: Breakdown of present value costs for systems designed case (a) to purify 100 gpd of water or case (b) to purify 100 gpd and provide 2 kwh of electricity for nighttime use. Total present value cost was \$731 for case (A) and.

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about doubled and the batteries became the primary contributor to total present value cost (77%). The unit cost for water produced (\$0.16 per 100 gallons) was obtained by annualizing the total present value cost over the 20-year design life of the system and dividing by the volume of water produced in a year. The unit cost of energy production (\$0.26 per kWh) was obtained from the difference in present value costs between systems with and without energy production constraints. That difference was annualized over the 20-year design life, and the annualized cost was divided by the annual nighttime energy use. Those results take on perspective when compared to the average cost of piped water in the United States (\$0.15 per 100 gallons) and the average household cost of electricity (0.13 per kWh).

Limitations and outlook

Although results of the study are suggestive, it is important to recognize their limitations. The problem posed, and therefore its solution, are site-specific in several respects. Most importantly perhaps, the curve representing solar irradiance is specific to latitude and season. It ignores the possibility of cloud cover during daylight hours. Overcoming each of these shortcomings will significantly increase the complexity of problem solution – making the problem more challenging, interesting and relevant. The solution put forward at this point pertains only to 36° north or south latitude, at the time of either equinox, on a clear day.

In addition, several problem parameters were selected arbitrarily. That is, the problem was solved for only one

membrane type – an NF membrane with a coefficient of permeation equal to $0.0157 \text{ L/s} \cdot \text{m}^2 \text{ atm}$. The ionic composition of the water to be treated is assumed to provide an initial osmotic pressure of 0.81 atm. Consideration of alternative raw water compositions might lead to selection of a larger or smaller recovery during NF, again altering the nature and cost of the optimal solution. Fortunately, problem parameters can easily be altered in order to find relevant solutions or be generalized in some way in order to investigate solution sensitivities to parameter selection. Finally, the discount operator used to account for the time value of money (here 0.05/year) was selected arbitrarily. Again, its effect could be subjected to a sensitivity analysis. Several system components were omitted from the objective function in the optimization problem because their size/cost is essentially invariant within the solution boundaries. Their inclusion is necessary, however, to find the overall present value cost of the optimal solar-NF system.

Each of these shortcomings is potentially significant but lies beyond the intent of this work, which is to demonstrate use of the computational method and tool for optimization of multicomponent systems for solar NF. Stochastic representations of weather, although important, are not considered due to the complexity of the related problem and statistical nature of the problem solution. It is an area that is ripe for additional effort.

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Ethical approval: The conducted research is not related to either human or animal use.

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