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Comparative assessment of evaporation models in algal ponds

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ABSTRACT

The ability to predict water evaporation from shallow ponds is needed to accurately assess the water demand and costs of microalgae farming. This study assessed the accuracy of seven evaporation models available in the literature against experimental data collected in a raceway algal pond located in Narbonne, France. A theoretical 'flat-plate' evaporation model and the "Sartori model" were identified as the most accurate models (errors of 14.2% and 9.2%, respectively, over a period of 274 days). As these two models require the mathematical determination of pond temperature, simulations were performed to determine if pond temperature could be substituted for air temperature to compute yearly evaporation estimates. Unfortunately, assuming that pond temperature was equal to air temperature caused significant inaccuracies on the yearly evaporation (e.g. up to 68% in an arid climate with the Sartori model). High-resolution co-modeling of evaporation and temperature is therefore required for accurate evaporation predictions.

1. Introduction

While the commercial potential of micro-algae cultivation is now well established [1,2], the environmental impacts of this biotechnology are still debated [3–5]. Of particular concern, algae cultivation can consume large amounts of fresh water (known as the water demand) due the free surface water evaporation when algae are cultivated in open ponds and/or if a significant amount of process water is not recycled back into the pond following biomass harvesting [6]. Fortunately, recent observations suggest that efficient process water recycling can be achieved without affecting algal productivity [7,8] and pond operation can be optimized to further reduce the amount of process water required [9]. Using best practice, the water demand of algal cultivation can therefore be expected to be mainly caused by evaporation losses from open ponds, the technology platform currently considered as the most economical solution for large-scale algal production [10,11]. It follows that the ability to predict water evaporation from shallow opaque ponds (where most of the light received is converted into heat, contributing then to increase evaporation) is needed to accurately assess the water demand and costs of microalgae farming. Unfortunately, while numerous modeling studies have attempted to develop tools to predict evaporation at the surface of open water bodies [12], there is no consensus on the best formula to use. In addition, it is often necessary to simultaneously predict pond temperature and evaporation, which can be technically difficult, because predicting evaporation requires knowledge of pond temperature and this data are often not available. The first objective of this study was therefore to comparatively assess the predictions of existing evaporation models against an independent data set collected in an algal raceway pond located in Narbonne, France. The second objective was to investigate if simple assumptions regarding pond temperature (such as assuming that the pond temperature is equal to the air temperature) could be used to predict evaporation without significant loss of accuracy.

2. Existing evaporation models

Numerous models predicting evaporation at the surface of open water bodies have been described in the literature for a large range of systems from small ponds to lakes (see the review of Sartori [12] for examples). Emphasis was given to theoretically-based models in the present study because these models are less dependent on empirical data and should therefore be applicable in a broad range of conditions: Section 2.1 presents the models selected for the comparative assessment based on this broad criterion. Section 2.2 details how each model accounts for forced and natural convection as the relative magnitudes of these two mechanisms are key to understand the level of accuracy of each model. Section 2.3 describes an approach to determine the height at which wind speed must be measured to predict evaporation because

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this parameter is often not specified in the literature, which causes uncertainty on evaporation predictions.

2.1. Model selection

Sartori [12] reviewed 19 evaporation models in order to select the most ‘universal’ model enabling accurate predictions over a large range of systems, from solar ponds to swimming pools. This author rejected eight models that did not account for air relative humidity, as evaporation rates are significantly impacted by this parameter, and a further six models yielding predictions that significantly differed from empirical observations. In particular, some of these rejected models accounted for the radiation reaching the pond surface. These models (see the review of Rosenbary et al. [13] or the recent study of Andreasen et al. [14] for examples) can be useful in cases where predicting the water temperature can be technically challenging, for example in stratified lakes. On the other hand, these models can also introduce some level of uncertainty as the impact of radiation on the water temperature depends on the depth of the water body due to thermal inertia. As a result these models can be highly specific to the site they were calibrated to. As models can accurately predict temperature for shallow well-mixed open ponds [15], using radiation-based models would introduce some unnecessary uncertainty. We further excluded a model (the “Jurges' model”) that did not account for the pond temperature in spite of its large impact on the evaporation rate. The remaining four models were included in our study:

- The “Sartori's model” [16] derived from theoretical considerations similar to the ‘flat-plate’ model described below;
- The “Carrier's model” [17] used by Taga et al. [18] to predict evaporation rates from solar ponds;
- The 'Ryan and Harleman's equation' [19] used by Alamanza and Lara [20] to predict the evaporation rate from a swimming pool;
- The “Molineaux's model” [21] empirically derived from evaporation measurements from swimming pools.

Tang and Etzion [22] later developed a model to predict evaporation rates at the surface of open water bodies and this model was used by Ali [23] to predict the temperature of insulated open tanks in arid climates. As this model satisfied the criteria proposed by Sartori [12], it was included in our comparative study.

Evaporation rates from algal ponds were predicted in previous assessments of the water demand associated with algal production. In some of these studies, evaporation was roughly estimated based on experimental observations at the location considered [24–26] but this approach cannot be used to predict evaporation at different locations and/or for different process configurations given the impact of climate, process design and operation on pond evaporation. The use of experimental ‘Class-A pan evaporation’ data [27] in other studies [28,29] was also deemed inaccurate because the water used in Class-A pans is clear and, therefore, significantly cooler than opaque algal cultures in ponds which absorb more light (meaning Class A evaporation data likely underestimate pond evaporation). Clarens et al. [30] used the Penman equation in order to assess the environmental impact of algal biodiesel production, but Sartori [12] showed that this equation significantly overestimates evaporation in ponds, and this equation was therefore not included here. In contrast, the evaporation equation established by Brady et al. [31] for open ponds, and later used by James and Boriah [32] and Wigmosta et al. [33] to predict temperature in algal ponds, and the theoretically-derived flat-plate model of Béchet et al. [15] used by Guieysse et al. [6] to determine evaporation rates from open ponds were selected for comparative assessment. Table 1 summarizes the seven models compared in this study.

2.2. Forced and natural convection

Two different mechanisms can cause evaporation from the surface of open water bodies: forced and natural convection. Forced convection results from the flow of a layer of relatively dry air above the water surface. Natural convection is caused by natural air buoyancy occurring when warmer air at the pond surface rises due to lower density, thus creating an ascending air movement. In outdoor conditions, the two mechanisms occur at the same time but their relative magnitudes depend on the water surface area and weather conditions. Forced convection is favored by high wind speed while natural convection needs two conditions to be significant: wind speed low enough to ensure that the buoyant air layer is not disrupted, and a significant temperature difference between air and water [34]. For this reason, most equations listed in Table 1 express evaporation as the sum of a ‘wind speed–dependent term’ representing forced convection and ‘wind speed-independent term’ representing natural convection.

2.3. Wind velocity height

Wind speed greatly impacts the rate of free-surface evaporation in open ponds (Table 1) so this parameter must be accurately inputted when predicting evaporation. Consequently, it is critical to know the height at which wind velocity must be inputted because wind velocity varies with height due to air friction at the ground/water surface [35]. In the empirical models listed in Table 1 (Eqs. (3) to (7)), the wind height at which wind speed must be inputted depends on how each model was initially designed and/or parameterized (see Table 1 for details). As weather stations usually measure wind velocity at a standard height above the ground surface (z_0, in m), the wind velocity at the height required by each model (z, m) can be determined using the correlation described by Gipe [35]:

$$v(z) = v_0\left(\frac{z}{z_0}\right)^{\alpha} \tag{8}$$

where v is the wind speed ($\mathrm{m\,s^{-1}}$) at the height z (m) and α is an experimental coefficient that depends on the environment in the pond vicinity (taken at 0.29 in this study, representative of a rural terrain [35]).

Determining the height at which wind speed must be measured is more complex in the case of theoretically-derived models (Eqs. (1) and (2); Table 1). Sartori [12] suggested this height was between 0.3 and 2 m but did not specify the value required in his model (Eq. (2), Table 1). In the following simulations this height was taken at 2 m in Eq. (2) as the author suggested this height as being one of the most commonly used in the literature. The ‘flat-plate’ model (Eq. (1), Table 1) was constructed on a theoretical case where the wind speed does not vary with height when reaching the edge of the open pond (the open pond being considered as a ‘flat plate’, hence the name of the model). As the wind speed varies with height in outdoor conditions, it is therefore unclear which speed should be used when this expression is applied to an outdoor pond. In this study, the wind speed was taken as equal to the wind speed at the top of the layer of air affected by the surface of the open pond, i.e. the ‘boundary layer’. This height (δ, m) or thickness of the boundary layer, was calculated according to Holman [36] as:

$$\delta = L(0.381{Re_L}^{-0.2} - 10256{Re_L}^{-1})\,for\;\; Re_L \geq 5.10^5 \tag{9a}$$

$$\delta = 4.64L{Re_L}^{-0.5}for\;\; Re_L < 5.10^5 \tag{9b}$$

where Re_L is the Reynolds number calculated for the pond length L (m). In practice, for the algal pond used in this study, the boundary layer thickness varies between 0.1 and 0.3 m depending on wind velocity, as calculated by Eqs. (9a) and (9b) (pond length of 10 m, the average between the size and length of the pond as shown in Fig. 1). Considering that water level varied between 0.05 and 0.35 m in this