Investigation of the biological treatability of pistachio processing industry wastewaters in a batch-operated aerobic bioreactor

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Received: 22 January 2022 / Accepted: 18 April 2022 / Published online: 12 May 2022
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Abstract
This study encompasses investigation of treatment of pistachio processing industry wastewaters in a batch reactor under aerobic conditions, calculation of kinetic parameters and comparison of different inhibition models. The mixed microorganism culture used in the study was adapted to pistachio processing industry wastewaters for nearly one month and then concentrations from 50 to 1000 mg L⁻¹ of pistachio processing industry wastewaters were added to the medium and treatment was investigated in batch experiments. The Andrews, Han-Levenspiel, Luong and Aiba biokinetic equations were chosen for the correlations between the concentration of pistachio processing industry wastewaters and specific growth rates, and the kinetic parameters in these biokinetic equations were calculated. The maximum specific growth rate, semi-saturated constant and inhibition constant parameters, included in the Aiba biokinetic equation providing best fit among the other equations, had values calculated as 0.25 h⁻¹, 19 mg L⁻¹, and 516 mg L⁻¹, respectively. The substrate value reaches maximum value and the specific growth rate at this concentration were calculated as 101.379 mg L⁻¹ and 0.1827 h⁻¹, respectively.

Keywords Aiba biokinetic equation · Biological treatment · Mathematical modeling · Pistachio processing industry wastewater

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Introduction

A member of the Anacardiaceae family, the pistachio includes only 11 species with the most economic species known to be *Pistacia vera L.* (Alma et al. 2004). The pistachio was first cultivated by the Hittites settling in southeastern Anatolia and spread to Rome in the first century and then on to Spain and France. The transition of pistachio to America occurred in 1853–1854 (Kashaninejad and Tabil 2011). The pistachio grows in suitable microclimates from the 30°–45° parallels in both north and south hemispheres of the globe (FAO 2018). Globally, countries producing pistachio are generally located in the northern hemisphere, and among these countries, Iran, USA and Turkey have shared the top three places in terms of production amounts for many years (FAO 2018). Pistachio yields product in an economic sense in regions with hot and dry summers (mean 25 °C), but very cool winters (mean 7.2 °C) (Ayfer 1990; Bilim and Polat 2006). Known as the king of nuts, pistachio may be described as a concentrated energy pill due to richness in proteins, vitamins and other minerals and nutritional features (Woodroof 1967). Pistachio contains twice the protein and four times the phosphorus compared to beef, in addition to being very rich in terms of potassium, iron, vitamin A and vitamin B1 (Woodroof 1967).

Pistachio harvest occurs in the second half of August and beginning of September in warm regions like Gaziantep and Şanlıurfa located in Turkey (Ayfer 1964; Onay and Jeffree 2000). Globally, the pistachio processing industry (PPI) is rapidly developing and Turkey is 3rd place in pistachio production after Iran and the USA (FAO 2018). In Turkey, a wet system is used to process pistachio and nearly 6 m³ wastewater per ton is formed (Fil et al. 2014). This rate shows variability linked to the size of the operation. Pistachio processing industry wastewater (PPIW) contains high organic matter with polluting properties like high chemical oxygen demand (COD), high total organic carbon (TOC) and high total phenol (Fil et al. 2014).

There are 6 separate stages followed in order to strip the pistachio of the outer red covering. These stages are soaking, flaking, washing and shellling, empty-full separation, drying and cracking processes, in order, and the processes in these stages are shown in Fig. 1 (Tırınk et al. 2020).

As seen in Fig. 1, investigations of the PPI show that mean 100 m³ day⁻¹ water is used during flaking and shellling. It is known that nearly 20 m³ wastewater may form after processing 1 ton of pistachio while this rate may vary linked to the size of the operation (Doğru 2013).

PPIW contains dense suspended solid matter and phenols in the structure, in addition to high organic matter with polluting properties. Treatment is very difficult due to the toxic pollutants and discharge of PPIW into the receiving environment without treatment causes serious environmental problems. Due to these environmental problems, many studies related to treatment of PPIW were completed in countries where production occurs, especially; however, there are very few studies. Among studies about recycling and treatment of PPIW, a study investigated the effect of domestic wastewater treatment using the active sludge process on PPIW (Khademí et al. 2018), in addition to studies listing chemical and biological alternatives like coagulation/flocculation (Tırınk et al. 2020), Fenton (Demir and Rastgeldi 2018; Bayar et al. 2018), electrocoagulation (Fil et al. 2012; Güzü 2014; Bayar et al. 2014; Yılmaz and Kόksal 2017; Isik et al. 2020), electrooxidation (Fil et al. 2012, 2014; Isik et al. 2020), and anaerobic treatment (Gür 2016; Ozay et al. 2018; Gür and Demirer 2019). As a result of the high chemical oxygen demand of PPIW, there are few studies encountered in the literature about aerobic treatment of PPIW.

As there are limited numbers of studies about treatment of PPIW, studies performed about similar wastewater will be a guide. Studies to be performed about this topic will contribute to the global literature while offering technological and economic choices for treatment of PPIW. This study investigated the biological treatment under aerobic conditions of...
wastewater due to production and processing of pistachio
cultivated in Gaziantep located in southeast Turkey. Addition-
ally, kinetic parameter values were calculated using data 
 obtained from experiments with mixed cultures under aer-
obic conditions.

Materials and methods

Wastewater and chemical matters

The PPIW used in the study was obtained from pistachio 
processsing factories located in Gaziantep province in two 
different periods and the wastewater characterization is 
shown in Table 1 (Tırınk et al. 2020). All chemical agents 
required for the study were obtained commercially (Merck 
and Sigma quality).

Experimental system

The study used a reactor with 500 mL volume for batch 
experiments and the experimental system is shown in Fig. 2. 
The mixing rate, medium temperature and pH values were 
chosen as 150 rpm, 25 ± 1 °C, and 7.5 ± 0.5, respectively. 
The reactor was continuously ventilated during batch experi-
ments with dissolved oxygen (DO) values kept above 2 mg 
L⁻¹.

Source of culture and culture media

The microorganisms used for removal in an aerobic medium 
for PPIW were obtained from active sludge from the precip-
itation pool of Erzincan Urban Wastewater Treatment 
Plant and from a continuously-fed milk industry wastewater 
feed tank. Later microorganisms were fed with PPIW as 
carbon source and attempts were made to ensure adaptation 
of microorganisms to the wastewater. To sustain the viability 
of microorganisms, a fluid culture medium with content given in Table 2 was used (Kul and Nuhoğlu 2020; Ucun 
et al. 2010).

Analytic techniques

During the study, total phenol (TP) concentration was 
determined with the Folin–Ciocalteau method (Folin and 
Ciocalteu 1927; Atanassova et al. 2005) with suspended 
solid matter (SSM) and microorganism concentrations (X) 
determined spectrophotometrically at 525 nm wavelength 
(Nuhoğlu and Yalçın 2005; Kul and Nuhoğlu 2020). Addi-
tionally, for confirmation, gravimetric microorganism con-
centrations were tested with the standard methods (APHA 
1995). Nitrate and nitrite concentrations were measured 
with a Dionex ICS 3000 brand ion chromatography device, 
while total organic carbon (TOC) and total nitrogen (TN) 
measurements were made with a Teldyne-Tekmar Apollo 
9000 analysis device. Phosphate analysis used ammonium 
vanadomolybdate with absorbance measured with a spectro-
photometer at 400 nm wavelength. The pH and temperature 
in the reactor were measured and recorded continuously with 
a WTW brand multiline P4 model multiparameter measure-
ment device according to the electrometric method. The DO 
amount was determined by dipping an oximeter probe into 
the sample according to the membrane electrode method. 
Other analyses were performed as shown in standard meth-
ods (APHA 1995).

Biological treatment and microbial kinetics

The performance of biological processes used for waste-
water treatment is linked to the dynamics of the substrate 
used and microbial growth. Thus, effective design and 
operation of systems requires an understanding of the 
基本 principles of biological reactions and microorgan-
ism proliferation. Kinetic models are used with the aim of 
defining the removal of nutritional material from wastewater 
within the framework of some basic assumptions. Most
biological treatment processes are very complex, operate within mutual interactions and contain mixed microbiological populations. For this reason, mathematical modelling of wastewater treatment systems is important to a very high degree. Microbial growth kinetics explain the substrate oxidation in a biological reactor and the production of biomass forming the total suspended solid concentration. The simplest and most-commonly used model for wastewater treatment is Monod kinetics, which is shown in Eq. (1) (Winkler 1981; Schugerl 1991; Tchobanoglous et al. 2003).

\[
\mu = \frac{\mu_{\text{max}} \cdot S}{K_s + S}
\]  

(1)

Here, \(\mu\) is the specific reproduction rate \((h^{-1})\), \(S\) is the substrate concentration (COD concentration in PPIW (mg L\(^{-1}\)), and \(K_s\) is the semi-saturated constant (mg L\(^{-1}\)).

The \(K_s\) and \(\mu_{\text{max}}\) values given in Eq. (1) vary according to the microorganisms used and the substrate type limiting growth in the medium. The Monod equation is mainly used to define reactions occurring at low rates with very high cell concentrations. In situations where the reaction occurs more rapidly, deviations develop in the Monod characteristic curve and it is inadequate to define the reaction kinetics. Different mathematical models like Andrews (Andrews 1968), Luong (Luong 1987), Han-Levenspiel (Han and Levenspiel 1988) and Aiba (Aiba et al. 1968) are successful in defining the effect of substrate inhibition on bacterial activity rates and these equations are shown in order in Eqs. (2)–(5). These equations are related to the specific growth rate, in addition to specific substrate consumption rates.

\[
\mu = \frac{\mu_{\text{max}} \cdot S}{K_s + S}
\]  

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**Table 2** Content of liquid culture media (for 100 g L\(^{-1}\) COD)

| Chemical agent                              | Unit | Amount |
|---------------------------------------------|------|--------|
| Ammonium sulfate \(((\text{NH}_4)_2\text{SO}_4)\) | mg L\(^{-1}\) | 72.22  |
| Magnesium sulfate \((\text{MgSO}_4\cdot7\text{H}_2\text{O})\) | mg L\(^{-1}\) | 10     |
| Iron III chloride \((\text{FeCl}_3\cdot6\text{H}_2\text{O})\) | mg L\(^{-1}\) | 0.1    |
| Manganese sulfate \((\text{MnSO}_4\cdot4\text{H}_2\text{O})\) | mg L\(^{-1}\) | 10     |
| Calcium chloride \((\text{CaCl}_2)\) | mg L\(^{-1}\) | 2      |
| Potassium phosphate \((\text{KH}_2\text{PO}_4)\) | mg L\(^{-1}\) | 50     |
| Potassium diphosphate \((\text{K}_2\text{HPO}_4)\) | mg L\(^{-1}\) | 100    |

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Here, $K_i$ is the inhibition constant (mg L$^{-1}$) and $S_m$ is the maximum substrate concentration (mg L$^{-1}$) that fully inhibits proliferation.

### Calculation of kinetic parameter values

After microorganisms were habituated to PPIW in the aerobic medium for nearly one month, batch experiments began. For batch experiments, the microorganism concentration ($X$, mg L$^{-1}$) was fixed, while different concentrations of PPIW ($S$, mg L$^{-1}$) were added to Erlenmeyer flasks and the variation in concentrations of $X$, $S$ and TP were monitored over time.

To calculate the specific reproduction rate ($\mu$) in this study, Eq. (6) was used. The logarithm of the concentration of $X$ varying over time in each experiment was obtained and the values were plotted on a graph against time and the $\mu$ values were calculated from the linear section of the slope.

Here, $X_t$ is the microorganism concentration at time $t$ (mg L$^{-1}$) and $X_0$ is the initial microorganism concentration (mg L$^{-1}$).

### Mathematical model

To model the variation occurring in $S$ and $X$ values in the batch reactor, the two-component Aiba-based biokinetic model was chosen. The mathematical expressions used to calculate $S$ and $X$ values are given in Eqs. (7) and (8).

$$\frac{dS}{dt} = -r_1$$  
(7)

$$\frac{dX}{dt} = r_2$$  
(8)

Using Eqs. (7) and (8), the reaction rates were organized as given in Eqs. (9) and (10).

$$r_1 = \frac{\mu_{max} \cdot S \cdot X}{(K_s + S)} \cdot \exp \left( -\frac{S}{K_i} \right)$$  
(9)

$$r_2 = \frac{\mu_{max} \cdot S \cdot X}{(K_s + S)} \cdot \exp \left( -\frac{S}{K_i} \right) - b \cdot X$$  
(10)

Here, $Y$ is the yield factor and $b$ is the death constant (h$^{-1}$).

The yield factor for substrate concentrations (dry biomass weight/substrate weight) was calculated using Eq. (11).

$$Y = \frac{\Delta X}{\Delta S}$$  
(11)

### Results

#### Removal from PPIW under aerobic conditions

For nearly one month, microorganisms used for removal from PPIW were habituated to PPIW under aerobic conditions. Later, initial microorganism concentrations were kept fixed and substrate with amounts varying from 50 to 1000 mg L$^{-1}$ were added and batch experiments began. During the study, mixing rate was 150 rpm, pH value was 7.5 ± 0.5 and temperature was set to 25 ± 1 °C. The variation over time for different initial $X$, $S$ and TP concentrations in the study is shown in Fig. 3.

Figure 3 shows the easily degraded organic portion of PPIW was consumed by microorganisms over time. As the initial concentration $S$ increased in the study, the adaptation time for microorganisms lengthened and in parallel with this, the removal durations of the $S$ concentrations increased.

#### Removal kinetics for PPIW in batch reactor under aerobic conditions

One of the most important points that requires care when revealing the proliferation kinetics of microorganisms is choosing the equation showing the correlation between $\mu$ and $S$. Data obtained from the graphs in Fig. 3 and with the aid of Eq. (6) calculated the $\mu$ value by taking the variation in the $X$ value over time. For each $S_0$ value, the $\mu$ values obtained in the exponential breeding phase and coefficients
using Eqs. (2)–(5) were obtained and shown in Table 3, along with the graphs in Fig. 4.

All these models mathematically express the inhibition effect of enzymes and substrates on proliferation of microorganisms. When deciding on the type of inhibition when attempting enzyme inhibition, the first step is determination of the inhibition type with graphic methods. Rapid development of computer technology in recent years has ensured linearization of enzyme inhibition kinetics and determination with non-linear regression solution techniques without

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requiring graphic methods. The non-linear regression solution techniques provide fit of experimental data to many inhibition models and selection of the most appropriate model is linked to a variety of assessment criteria. Statistical parameters are one of these assessment criteria. In the literature, there are many studies related to proliferation of microorganisms in the presence of inhibitors. In these studies, many parameters like μmax, Ks, and Ki can be determined with graphic methods or with non-linear regression solution techniques (Antunes et al. 2003).

Assessment of results obtained after kinetic analyses used the boundary conditions included in Table 4 (Luong 1987). Among models abiding by the boundary conditions, the kinetic coefficients for the model with smallest \( \sum (\mu - \mu_i)^2 \) total were taken and the model with best fit to experimental results were identified using Table 3. Here, \( \mu^e \) is the largest μ value measured during experiments.

### Table 3 Kinetic parameters obtained after modeling

| Model       | \( \mu_{\text{max}} \) | Ks    | Ki    | \( S_m \) | m   | n   | \( R^2 \) | \( \sum (\mu - \mu_i)^2 \) |
|-------------|------------------------|-------|-------|-----------|-----|-----|----------|-----------------------------|
| Andrews     | 1.1257                 | 126.969 | 53.7951 | –         | –   | –   | 0.9542   | 1.35 \( \times 10^{-3} \)   |
| Luong       | 0.1894                 | 4.6084 | –     | 1000      | –   | 1.0908 | 0.9653   | 1.39 \( \times 10^{-3} \)   |
| Han-Levenspiel | 0.1896               | 5.6131 | –     | 1000      | 1   | 1.0991 | 0.9653   | 1.39 \( \times 10^{-3} \)   |
| Aiba        | 0.2517                 | 19.9013 | 516.4340 | –         | –   | –   | 0.9827   | 4.9 \( \times 10^{-4} \)    |

### Fig. 4 Fit of data obtained from PPIW with biological substrate inhibition models

### Table 4 Boundary conditions

- \( K_s \leq K_i \)
- \( \mu^e \leq \mu_{\text{max}} \leq 3\mu^e \)
- \( K_s \leq 1000 \text{ mg L}^{-1} \)
The biokinetic parameters ($\mu_{\text{max}}, K_s, K_i, S_m, n$ and $m$) calculated with the Andrew, Luong, Han-Levenspiel and Aiba models in studies with similar wastewater and in this study are comparatively presented in Table 5.

As can be seen in Table 5, pure and mixed cultures were used to obtain the kinetic profile in biodegradation processes. The $\mu_{\text{max}}$ value calculated in this study was identified as 0.2517 h$^{-1}$ according to the Aiba biokinetic model with best fit. Additionally, the $K_s$ value in this study was 19.9013 mg L$^{-1}$ which is relatively smaller than values calculated in other studies. The $K_i$ value was 516.434 mg L$^{-1}$ which shows that PPIW may have inhibitory effects at relatively higher concentrations.

### Investigation of fit with Aiba model

Equations (9) and (10) were solved at the same time to calculate the model for variations in $S$ and $X$ values within the reactor over time. Equations (9) and (10) used the Aiba model coefficients. The model accepting $Y = 0.32$ g g$^{-1}$ and $b = 0.001$ h$^{-1}$ was applied to initial concentrations from 50 to 1000 mg L$^{-1}$. Results obtained at the end of experiments may be seen in Fig. 5.

**Table 5** Comparison of calculated biokinetic parameters with data obtained from similar wastewater

| Wastewater       | Model          | $\mu_{\text{max}}$ (h$^{-1}$) | $K_s$ (mg L$^{-1}$) | $K_i$ (mg L$^{-1}$) | $K$ (mg L$^{-1}$) | $S_m$ | $n$ | $m$ | References         |
|------------------|----------------|------------------------------|---------------------|---------------------|-------------------|------|-----|-----|-------------------|
| Olive Mill       | Aiba           | 0.302                        | 22.306              | 623.496             | –                 | –    | –   | –   | Kul and Nuhoğlu (2020) |
| Wastewater       | Haldane        | 0.428                        | 45.335              | 207.967             | –                 | –    | –   | –   | Tseng (2020)         |
|                  | Tsenng         | 0.099                        | 79.563              | 0.1                 | –                 | 1.802| –   | –   | Yano and Koga (2020)  |
|                  | Yano and Koga  | 0.18                         | 3.613               | 1327.466            | 1189.181          | –    | –   | –   |                    |
| Tannins          | Haldane        | 0.545 ± 0.194                | 0.119 ± 0.065       | 0.234 ± 0.129       | –                 | –    | –   | –   | Tramšek et al. (2006) |
|                  | Edwards        | 0.319 ± 0.045                | 0.066 ± 0.013       | 0.732 ± 0.168       | –                 | –    | –   | –   |                    |
|                  | Luong          | 0.358 ± 0.061                | 0.063 ± 0.019       | –                   | 0.972 ± 0.338     | 0.832±0.666| –   | –   |                    |
|                  | Aiba           | 0.481 ± 0.081                | 0.096 ± 0.027       | 0.557 ± 0.086       | –                 | –    | –   | –   |                    |
| Cellulose        | Andrew         | 0.536                        | 2.43                | 2.42                | –                 | –    | –   | –   | Agarwal et al. (2009) |
| production       | Han-Levenspiel | 0.162                        | 58.73               | –                   | 14.91             | 0.622| 34.98| –   |                    |
|                  | Luong          | 0.367                        | 2.48                | –                   | 1681              | 220.1| –   | –   |                    |
|                  | Aiba           | 0.369                        | 2.49                | 7.59                | –                 | –    | –   | –   |                    |
| Phenol           | Han-Levenspiel | 0.2901                       | 252.1               | –                   | –                 | 720  | 1   | 1   | Dey and Mukherjee (2010) |
| removal          | Luong          | 0.1291                       | 59.39               | –                   | –                 | 1148 | 0.9 | –   |                    |
|                  | Aiba           | 0.2579                       | 200.3               | 502                 | –                 | –    | –   | –   |                    |
| Phenol           | Han-Levenspiel | 0.0238                       | 46.67               | –                   | 400               | 2.1  | 1   | 1   | Saravanan et al. (2011) |
| removal          | Luong          | 0.0257                       | 40.55               | –                   | 400               | 0.6  | 1   | –   |                    |
| PPIW             | Andrew         | 1.1257                       | 126.97              | 53.7951             | –                 | –    | –   | –   | This study          |
|                  | Han-Levenspiel | 0.1896                       | 5.6131              | –                   | 1000              | 1.099| 1   | –   |                    |
|                  | Luong          | 0.1894                       | 4.6084              | –                   | 1000              | 1.099| –   | –   |                    |
|                  | Aiba           | 0.2517                       | 19.9013             | 516.434             | –                 | –    | –   | –   |                    |

Figure 5 shows the values obtained for experiments with different $S_0$ concentrations with $S$ and $X$ values in the reactor found with simultaneous solution of a 2-component simple model range. The real-time increase in $S$ and $X$ values found higher values than in the model. Profiles obtained using the same model coefficients for $S$ and $X$ showed deviations from these values. To improve these deviations, the Berkeley Madonna program curve-fit feature was used and the program was operated again with $b = 0.0005–0.008$ h$^{-1}$ and $Y = 0.2–1$ g g$^{-1}$. The mean of the different $Y$ and $b$ values found for wastewater concentrations between 50–1000 mg L$^{-1}$ were 0.3 g g$^{-1}$ and 0.0005 h$^{-1}$, respectively. The results obtained with these new optimum $Y$ and $b$ values can be seen on Fig. 6.

Due to the complicated compounds in PPIW, none of the trialed models were successful in reflecting the measured substrate variation profiles. All of the trialed models predicted that the substrates would be degraded in shorter durations. Contrary to this, as can be seen on graphs obtained using this data, the model appears to be successful in showing the X variation.

Of the three biokinetic constants included in the Aiba biokinetic equation, $K_i$ measures the inhibition intensity.
caused by the inhibitory material, $K_i$ is the semi-saturated constant and $\mu_{\text{max}}$ value explains half of the measured $S$ concentration. The $K_s$ value also shows the affinity of the microorganism for the substrate. Additionally, if there is a substrate inhibitor, it is not possible to observe the real $\mu_{\text{max}}$ value. Thus, $K_s$ gains an assumptive meaning. In this situation, if $\frac{d\mu}{dS} = 0$, the $S$ value reaches maximum value ($S^*$) and the $\mu$ value ($\mu^*$) at this concentration must be calculated as given in Eqs. (12) and (13) (Nuhoğlu and Yalçın 2005; Kul and Nuhoğlu 2020).

$$S^* = \sqrt{K_i K_s}$$  \hspace{1cm} (12)

$$\mu^* = \frac{\mu_{\text{max}}}{2\left(\sqrt{\frac{K_s}{K_i}} + 1\right)}$$  \hspace{1cm} (13)

The inhibition value given in Eq. (13) reflects not just the $K_i$ value but also the $K_s/K_i$ ratio. Large $K_s/K_i$ and small $\mu^*$ values are associated with $\mu_{\text{max}}$, and this is the largest inhibition degree (Nuhoğlu and Yalçın 2005). Using the kinetic
constant values calculated for $\mu_{\text{max}}$, $K_s$ and $K_i$ with the aid of Eqs. (12) and (13), the $S^*$ and $\mu^*$ values were calculated as 101.379 mg L$^{-1}$ and 0.1827 h$^{-1}$, respectively (Nuhoğlu and Yağm 2005; Kul and Nuhoğlu, 2020). The graphs obtained with the aid of these calculated values are shown in Fig. 7.

When Fig. 7 is investigated, all the trialed models predicted the substrate would be degraded in shorter durations. Contrary to this, as can be seen from graphs
Fig. 7 Fit of Aiba biokinetic model with data obtained using $S^*$ and $\mu^*$
obtained using data for the model, more successful graphs were obtained when the $S^*$ and $\mu^*$ values were used to show $S$ and $X$ variations.

**Discussion**

Wastewater characterization and biodegradability of PPIW, values of various kinetic models, and mathematical modeling of the time dependent behavior of substrate and microorganism concentrations were investigated. The PPIW characterization results confirmed that our findings lie well within the range given in the literature. The effect of initial substrate concentrations on microorganisms was evaluated to reflect the $S$-$\mu$ relationship and to gain insight into substrate removal performance in a batch-operated aerobic bioreactor. As an usual finding of many bioconversion studies, increased substrate concentration conferred higher removal times for PPIW in our study. The Andrews, Han-Levenspiel, Luong and Aiba biokinetic equations were chosen for the association between initial PPIW concentration and specific growth rate and the kinetic parameters in these equations were calculated. Considering the regression coefficients ($R^2$) and $\sum(\mu-\mu_i)^2$ values for the curves drawn using the model equations and kinetic parameter values, the biokinetic equation with best fit among the equations were the Aiba.

The $\mu_{\text{max}}$ is a parameter for modeling microbial growth under certain conditions. The $K_v$ value in this study which is relatively smaller than values calculated in other studies, which may be explained by the high affinity of the mixed culture for PPIW. The $K_i$ value showed that PPIW could have inhibitory effects at relatively higher concentrations. The literature shows that differences observed between biokinetic coefficients may be linked to many factors like environmental factors, differences in dominant microbial species and degree of adaptation of microbial cultures to wastewater. After adopting the Aiba based kinetic model, mathematical simulations were performed to test the performance of the batch reactor over time, taking into account the measured substrate and microorganism concentrations. The kinetic results obtained in this study can be used in the design of aerobic systems to be used for the treatment of similar wastewater. When high strength wastewaters like Pistachio processing wastewaters are aerobically degraded, the need for aeration equipments having high oxygen transfer capabilities is inevitable. With conventional systems, a fast enough oxygen transfer to purify high organic pollution may not be possible. In addition, in conventional aerobic systems such as continuous systems using final settling ponds, it may not be possible to reach a high enough microorganism concentration to decompose highly concentrated organic matter.

Large $K_v/K_i$ and small $\mu^*$ values are associated with $\mu_{\text{max}}$ and this is the largest inhibition degree. Using the kinetic constant values calculated for $\mu_{\text{max}}, K_v$ and $K_i$, the $S^*$ and $\mu^*$ values were calculated as 101.379 mg L$^{-1}$ and 0.1827 h$^{-1}$. It appeared that the simulation operated with these values were much more efficient. Since there are few mixed culture aerobic studies for PPIW in the literature, our study can be considered comprehensive in terms of testing various kinetic models and mathematical simulations.

**Acknowledgements** The authors are grateful for laboratory support from Ataturk University Department of Environmental Engineering.

**Author contributions** ST and AN conceived and designed research. ST conducted experiments. ST and SK analyzed data. SK wrote the manuscript. All authors read and approved the manuscript.

**Data availability** Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

**Declarations**

**Conflict of interest** Sevtap Tırnak declares that she has no conflict of interest. Alper Nuhoglu declares that he has no conflict of interest. Sinan Kul declares that he has no conflict of interest.

**Research involving human and animal rights** This article does not contain any studies with human participants or animals performed by any of the authors.

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