trode, while the cathode was used as the counter and the reference electrode.

2.3.2. Potential sweeps

Potential sweep experiments were carried out at a scan rate of 0.1 mV/s from the open-circuit cell voltage V_o, where the current $I = 0$, to the short-circuit cell voltage $V_{sc} = 0$, where the current has its maximum value I_{sc}. Power (P)–V curves were calculated from the V–I curves. From these P–V curves, the cell voltage V_{max} at which the maximum power was obtained was determined. The cell voltage at which half the maximum power was obtained (V_1) was determined in such a way that $V_{max} > V_1 > V_{sc}$.

3. Results and discussion

Electrochemical impedance and potential sweep measurements were performed in buffer and lactate (A1) or buffer, lactate and MR-1 (A2) as anolyte using MFCs with and without SS balls in the anode compartment.

The impedance spectra for the anode and cathode at their corresponding OCPs are shown in Fig. 1 for both anolytes. The EIS data are displayed as Bode plots, where the logarithm of the impedance modulus |Z| and the phase angle are plotted vs. the logarithm of the frequency f of the applied ac signal.

The impedance spectra of both the anode and the cathode follow a one-time constant model (OTCM), in which the solution resistance (R_s) is in series with a parallel combination of the capacitance of the electrode (C) and its polarization resistance (R_p) [10].

Table 1
Fit-parameters for the impedance spectra of the anode for anolytes A1 and A2

Fit-parameter	Anode		Cathode	
	A1	A2	A1	A2
R_p (Ω)	7.79×10^6	1.02×10^4	8.32×10^3	8.51×10^3
C (F)	9.22×10^{-4}	9.70×10^{-4}	6.22×10^{-2}	6.62×10^{-2}
R_s (Ω)	1.5	1.1	5.5	5.3

The impedance spectra of the anode in A1 were capacitive in the entire frequency region except in the high-frequency region, which is dominated by R_s. The addition of MR-1 to the anolyte (A2) caused a marked decrease of the polarization resistance of the anode (R_p^a) that was accompanied by a large decrease of its OCP.

The Bode plots for A1 as anolyte show qualitatively that R_p^a was much larger than R_p^c and that R_p^a decreased markedly as MR-1 was added to the anolyte (Fig. 1). The much higher capacitance value for the cathode (C^c) is due to the higher active surface area of the Pt-plated graphite cathode (Fig. 1) [10,15,16]. Recording of C^c is used as a quality control test to ensure that the Pt loading is the same for each new cathode. The fact that C^c remained more or less constant during the various tests discussed here suggests that contamination of the cathode due to possible crossover of the anolyte did not occur.

The EIS data shown in Fig. 1 were analyzed using the OTCM in the ANALEIS software developed by Shih and Mansfeld [12,17,18]. The fit-parameters of the impedance spectra of the anode and cathode shown in Fig. 1 are summarized in Table 1 for both anolytes. The most significant result of this analysis is the large decrease of

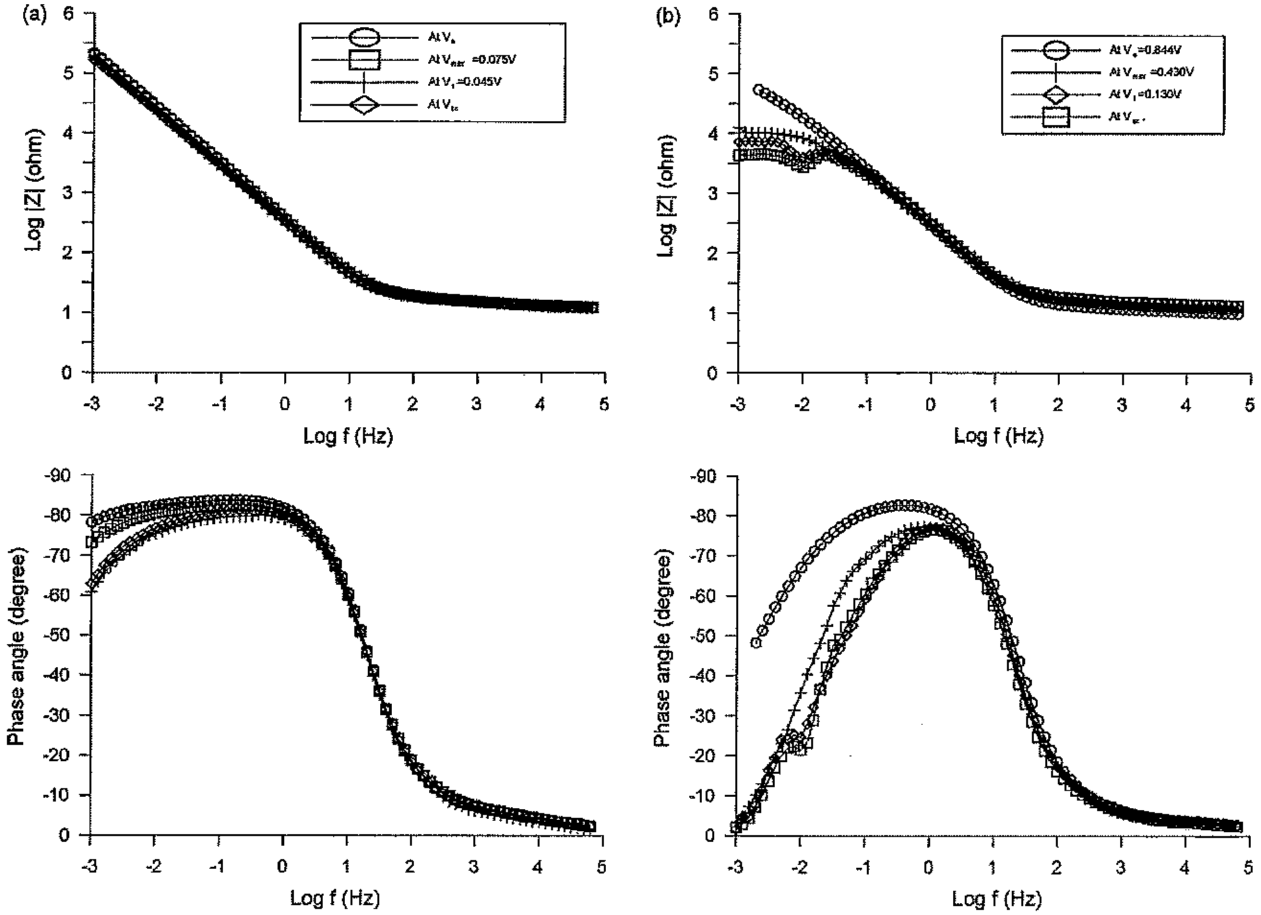

Fig. 2. Bode plots for the MFC obtained at different cell voltages with (a) buffer and lactate and (b) buffer, lactate and MR-1 as anolyte.

Table 2
Fit-parameters for the impedance spectra at different applied cell voltages for anolytes A1 and A2

Fit-parameter	V_o		V_{max}		V_1		V_{sc}	
	A1	A2	A1	A2	A1	A2	A1	A2
R_p^{cell} (Ω)	9.79×10^6	7.20×10^4	2.94×10^6	9.81×10^3	1.50×10^6	7.24×10^3	5.23×10^5	4.58×10^3
C^{cell}(F)	7.11×10^{-4}	7.84×10^{-4}	7.28×10^{-4}	9.24×10^{-4}	8.33×10^{-4}	9.13×10^{-4}	1.03×10^{-3}	7.11×10^{-4}
R_s^{cell} (Ω)	14.6	14.2	14.6	13.4	14.7	12.8	14.2	11.7

R_p^a in the presence of MR-1 (Table 1). The polarization resistance, R_p is inversely proportional to the exchange current density i_o of the redox reaction taking place in an electrode. The decrease in R_p^a after the addition of MR-1 signifies a large increase of the exchange current density of lactate oxidation in the presence of MR-1 in the anode compartment. C^a did not change when MR-1 was present in the anolyte. Similar results have been observed when different bacteria were used to inhibit corrosion of several materials [19,20]. The slightly lower solution resistance in the anode compartment (R_s^a) is due to the presence of sodium lactate in the anolyte which increases its ionic conductivity.

The impedance spectra of the MFC recorded in A1 and A2 at the four different applied cell voltages are shown in Fig. 2a and b. A comparison of the spectra in Fig. 2a and b demonstrates that the decrease of the dc limit of the impedance with applied cell voltage was much larger in the presence of MR-1.

The fit-parameters of the impedance spectra shown in Fig. 2a and b are listed in Table 2. $R_p^{cell} = R_{int}$ decreased in both A1 and A2 as the applied cell voltage was decreased due to the increase of the rate of lactate oxidation taking place at the anode and oxygen reduction at the cathode as the cell current increases. The capacitance values in Table 2 did not show significant variations with the applied cell voltage for the tests in both anolytes. The solution resistance R_s^{cell} (Table 2) was larger than R_s for the anode and cathode (Table 1) since it contains the contribution from the membrane resistance R_m [10].

The cell voltage–current (V–I) curves and the power–current (P–I) curves for the MFC with buffer and lactate as the anolyte are shown in Fig. 3a. The open-circuit cell voltage (V_o) was 160 mV. The maximum current I_{sc} that could be obtained from the cell was 0.17 μA (0.008 μA/cm²). The maximum power P_{max} = 6 nW (0.30 nW/cm²) was obtained at a cell voltage V_{max} = 75 mV (Fig. 3a). The addition of MR-1 to the anode compartment increased V_o to 844 mV, I_{sc} was 105 μA (5.2 μA/cm²) and P_{max} increased to more than 20 μW (1 μW/cm²) (Fig. 3b).

The Bode plots for the anode and the cathode in A1 and A2 for the MFC with SS balls added to the anode compartment are shown in Fig. 4. The impedance spectra of the anode showed a two-time constant behavior, where R_s is in series with two parallel combinations of a resistance and a capacitance (R_1, C_1 and R_2, C_2). As observed before (Fig. 1), the addition of MR-1 to the anolyte caused a marked decrease of the OCP of the anode. The impedance spectra of the cell recorded in both anolytes at four different applied cell voltages also showed a two-time constant behavior (Fig. 5a and b).

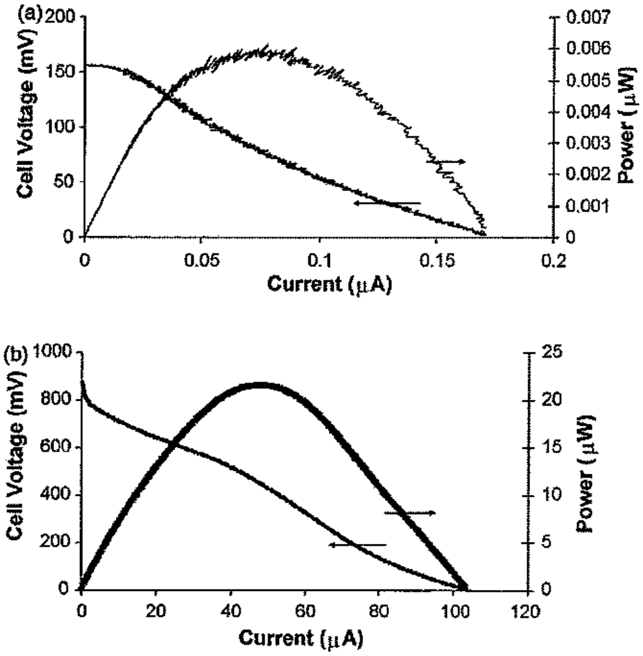

Fig. 3. V–I and P–I curves for the MFC with (a) buffer and lactate and (b) buffer, lactate and MR-1 as anolyte.

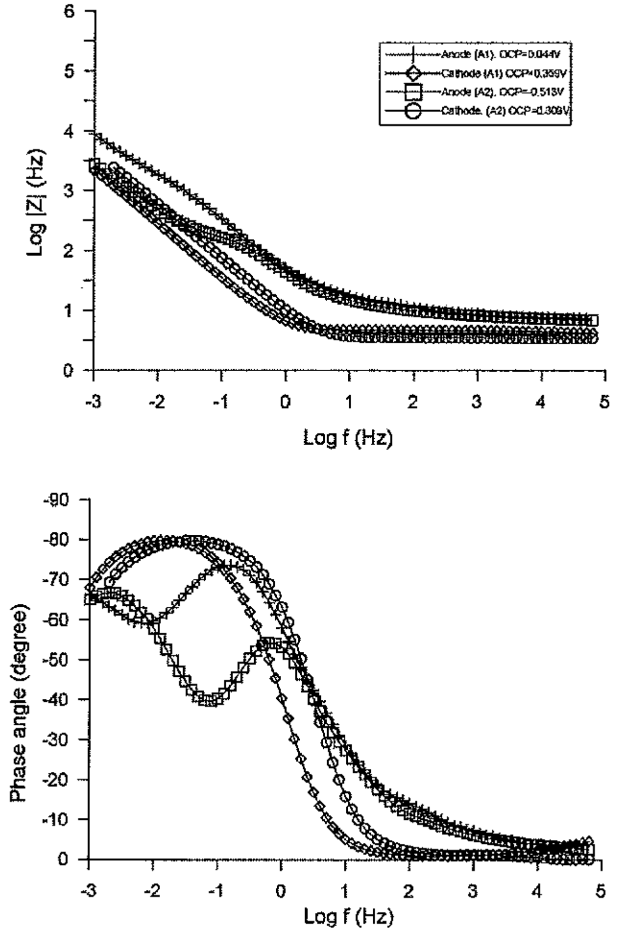

Fig. 4. Impedance spectra for the anode with SS balls and the cathode for the two different anolytes.