Bioresources and Bioprocessing

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Bioleaching of heavy metals from printed circuit board (PCB) by *Streptomyces albidoflavus* TN10 isolated from insect nest

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Abstract

Background: E-waste management is extremely difficult to exercise owing to its complexity and hazardous nature. Printed circuit boards (PCBs) are the core components of electrical and electronic equipment, which generally consist of polymers, ceramics, and heavy metals.

Results: The present study has been attempted for removal of heavy metals from printed circuit board by metal-resistant actinobacterium *Streptomyces albidoflavus* TN10 isolated from the termite nest. This bacterium was found to recover different heavy metals (Al 66%, Ca 74%, Cu 68%, Cd 65%, Fe 42%, Ni 81%, Zn 82%, Ag 56%, Pb 46%) within 72 h under laboratory conditions. The metal content of PCB after bioleaching was analyzed by ICP-MS. The crude PCB and bioleaching residue were characterized by FT-IR, XRD, SEM for the determination of structural and functional group changes for confirmation of bioleaching.

Conclusion: The findings of the present study concluded that *Streptomyces albidoflavus* TN10 is a promising candidate for bioleaching of heavy metals from the printed circuit board as an eco-friendly and cost-effective process.

Keywords: E-Waste, Printed circuit board, Heavy metals, Bioleaching, *Streptomyces* sp.

Introduction

Environmental pollution keeps on increasing at an alarming rate due to several man-made activities such as urbanization, technological advancement, unsafe agricultural practices and rapid industrialization (Ojuederie and Babalola 2017). Modern life is highly attracted to new and sophisticated electronic equipment with innovative technology. Moreover, the increasing necessities of mankind, the decreasing cost of electronics and the fast rate at which the outdated units are replaced have given rise to the generation of a new stream of waste known as E-waste which is rising three times higher than the other forms of municipal waste (Adie et al. 2014). Globally, about 50 million tons of e-waste are produced every year (Liu et al. 2016). Waste electrical and electronic equipment (WEEE), also called electronic waste or e-waste, has been attracting more and more concerns from scientists, entrepreneurs, journalists and governments all over the world (Yazici and Deveci 2013).

Printed circuit board is an important and essential component of all electronic and electrical equipment, containing lots of valuable metals together with the number of hazardous metals or minerals which can harm the environment as well as human health (Karwowska et al. 2014; Ilyas and Lee 2014; Willner et al. 2015). Therefore, there is an urgent need for the recovery of valuable metals from PCBs. Various processes, such as mechanical (Meng et al. 2017), pyrometallurgical (Jung et al. 2017), hydrometallurgical (Pant et al. 2012) and biometallurgical (Mrazikova et al. 2016; Priya and Hait 2017) process, are applied for the recovery of metals from PCBs. The recovery of heavy metals using pyrometallurgical and

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hydrometallurgical methods releases toxic gases such as dioxins and furans which affect the environmental and public health. Bioleaching is a promising technology that uses microorganisms to recover metals from PCB which is low cost and ecofriendly (Hong and Valix 2014). Among the all microorganisms being selected for bioleaching of metals from PCB, chemolithoautotrophs are commonly used for metal recovery from PCBs, such as *Acidithiobacillus ferrooxidans*, *Leptospirillum ferrooxidans, Acidithiobacillus thiooxidans* (Erust et al. 2013) and *Chromobacterium violaceum* (Li et al. 2015).

Actinobacteria are the group of ecologically abundant and metabolically multitalented bacteria that are widely distributed in nature including the metal-contaminated soils. They are well known for their ability to produce secondary metabolites and wealth of natural products with structural complexity and with diverse medicinal applications and properties (Abdelmohsen et al. 2014). Members of the phylum actinobacteria are well explored for their ability to degrade several recalcitrant chemicals like hydrocarbons, pesticides and industrial dyes (Polti et al. 2014). There are several studies which reported regarding the heavy metal resistance (Latha et al. 2015) and bioaccumulation (Lin et al. 2012) potential of actinobacterial genera, notably the genus Streptomyces. However, they are not much investigated for bioleaching of heavy metals from e-wastes including from PCBs. With this view, the present study focused on heavy metal bioleaching from printed circuit board using metal-resistant actinobacterium isolated from an insect nest, an understudied source.

Materials and methods

Collection and processing of e-waste

Printed circuit boards (PCBs) were collected from the e-waste dumping area at Chennai (Long. 80° 7′ 39″; Lat. 12° 55′ 37″), Tamil Nadu and India. No physical or mechanical separation process was used before transportation to the laboratory. Therefore, it is necessary to first remove as much of the chemical coating as possible. PCBs were transferred in 10-M NaOH solution and left undisturbed for 48 h. Then, PCBs were taken out and washed under running tap water to remove the solder. The treated PCBs were kept in tray dryer for 40 min and finally sieved for fine powder with 120-µm pore size for analysis and bioleaching (Jadhav et al. 2016).

Determination of metal content of PCB

Five grams of PCB powder was taken in 250-ml Erlenmeyer flask and mixed with 40-ml aqua-regia [a mixture of concentrated acid (69% m/v) and hydrochloric acid (37% m/v) at 1:3 ratios]. The mixture was allowed to stand for 24 h and centrifugation was carried out at 5000 rpm for 15 min. The digested PCB solution was then filtered through a 0.45-µm membrane filter. The metal concentration of PCB powder was analyzed using ICP-MS (Agilent 7700X ICP-MS G3281A) (Yamane et al. 2011).

Description of actinobacterial strain

Actinobacterial strains for bioleaching studies were obtained from the Bioprospecting division, Centre for Drug Discovery and Development, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India. All the strains were previously isolated from termite nest (Lat.79.69; Long.12.83) collected from Kanchipuram, Tamil Nadu, India. Pure cultures of all the strains were maintained in ISP 2 medium as well as in 30% glycerol stored at − 20 °C for further studies (Radhakrishnan et al. 2014).

Screening and identification of heavy metal resistance actinobacteria

The metal tolerance pattern of actinobacterial strains was determined by the minimum inhibitory concentration (MIC) approach. ISP2 agar plates with 100–1500 ppm of heavy metal ($FeSO_4$, $CuSO_4$, and $NiCl_3$) concentrations were prepared. Spores of actinobacterial strains were inoculated on all the heavy metal-supplemented ISP2 agar plates as a spot. The growth of actinobacterial strains was observed after incubation at 28 °C for 1 week and their heavy metal-resistant properties were recorded. For identification, microscopic, cultural and physiological characteristics of strain TN10 were studied described by Shirling and Gottileb (1966) and Radhakrishnan et al. (2013). Effect of physiological conditions like the addition of sugars, aminoacid, pH, temperature (°C) and NaCl concentration of potential actinobacterial strain TN10 was also studied. For the 16s rRNA sequence analysis, genomic DNA from the actinobacterial strain TN10 was isolated using solute ready genomic DNA kit. Concentration and purity of the extracted DNA were then evaluated by running on agarose gel and by NanoDrop (Thermo Scientific) readings. The genomic DNA obtained from the actinobacterial strain TN10 was further subjected to PCR amplification of 16S rRNA gene using the primers 8F (5′-AGA GTT TGA TCC TGG CTC AG-3′) and 1492R (5′-GGT TAC CTT GTT ACG ACT T-3′) (Lane 1991). The reaction mixture (50 µl) consisted of 100 ng of 2-µl genomic DNA, 5 µl of 10× buffer, 4 µl of BSA (1 mg/ml), 1 µl of dNTP mixture (25 mM), 1 µl of each primer (10 µM) and 3.5U of Taq DNA polymerase. PCR condition provided as 6 min at 94 °C followed by 35 cycles of 45 s at 94 °C, 45 s at 55 °C and 1.5 min at 72 °C, followed by an 8 min extension at 72 °C. PCR amplification was performed in an Eppendorf Master cycler Gradient.

Purified PCR product was sequenced bi-directionally to obtain complete coverage at Eurofins Genomics, Bangalore. Sequences were edited and contig was assembled in DNA baser v.3 and compared with GenBank sequences by BLAST analysis. The 16S rRNA gene sequence was aligned with selected sequences obtained from the GenBank using the CLC sequence viewer 6.0 program. Phylogeny prediction was done using MEGA 7 software (Saitou and Nei 1987). The confidence values for the branches of the phylogenetic tree were determined using bootstrap analyses (Felsenstein 1985) based on 1000 resampling of the neighbor-joining data set. The partial 16S rRNA nucleotide sequence of the potential actinobacterial strain TN10 was deposited in the GenBank database.

Bioleaching of heavy metals from the printed circuit board (PCB)

Actinobacterial strain TN10, that showed resistance to the most concentration of significant metals in primary screening, was inoculated into 200 ml of yeast extract malt extract broth in 500-ml conical flask and incubated at 28 °C in 120 rpm in shaking incubator for 24–48 h. After incubation, the cells were separated by centrifugation of culture broth at 10,000 rpm for 10 min. The pellet was taken and washed two times with sterile distilled water. One gram of crude PCB powder was added into each 150 ml of ISP 2 broth medium taken in three 500-ml conical flasks and pH of the medium was adjusted to 5, 6 and 7, respectively. Then, 48-h fresh culture of actinobacterial strain TN10 was inoculated into PCB containing solution. The flasks were kept in a rotary shaker at 110 rpm for 120 h. Then, the sample was drawn aseptically at every 24 h. Cells were separated by centrifugation at 10,000 rpm for 20 min and the cell-free supernatant was collected in clean tubes and used for analysis. Bioleaching of heavy metals from the crude PCB was determined by ICP-MS analysis (Agilent 7700X ICP-MS instrument (Model#-G3281A) The percentage of heavy metals accumulation was calculated using the formula (Jadhav et al. 2016). % heavy metal extraction = Initial metal content − metal content after leaching/initial metal content × 100.

Characterization of PCB and bioleaching residue

SEM analysis

Dried PCB powder and its bioleaching residue were subjected to SEM analysis by the following method of Ijadi Bajestani et al. (2014). The bioleaching residue was washed five times and then dried at 80 °C. PCB and bioleached residue were mounted with 2.5% glutaraldehyde for 60 min and washed with 0.1-M sodium acetate buffer (pH 7.3). Sample was dehydrated over an ethanol gradient and examined with a QUANTA 200(Netherlands).

XRD analysis

XRD pattern of PCB powder and its bioleached residue was analyzed by adopting the method described by Wang et al. (2011) with a slight modification and the peaks from the results were compared by standards of JCPDS records (Garg et al. 2019).

FT-IR analysis

Dried PCB and the bioleaching residues were investigated by Fourier transform infrared spectroscopic (FTIR) analysis. The bioleaching residues were taken and centrifuged at 15,000 rpm for 15 min and the pellets were washed three times with phosphate buffer (pH 7.0) and dried in 60 °C. The dried PCB and bioleached residue were mixed with spectroscopically pure KBr in the ratio of 2:200, pellets were fixed in a sample holder and the analyses were carried out using Perkin Elmer Spectrum RXI FTIR Spectrometer in the mid-IR region of 400–4000 cm^{-1} with 16 scan speed (Xia et al. 2018).

Statistical analysis

Bioleaching experiments are conducted in triplicates ($n = 3$) and the percentage of metal removal from the printed circuit board was calculated with error bars. Both mean and standard deviation were performed where appropriate, using the statistical package with graph bad prism version 8.

Result and discussion

Sample collection and determination of metal content of PCB

E-waste is one of the important sources of heavy metal pollution which contains a wide range of metals including precious metals like gold and silver, hazardous metals like arsenic and mercury, and base metals like copper and nickel (Pradeepa et al. 2017). The waste discarded PCBs were collected from Chennai corporation waste disposal site. Chennai is one of the four metropolitan cities in India and is a large generator of e-waste by numerous industries. The heavy metals present in the collected PCB are given in (Table 1). The results of ICP-MS analysis showed that copper (Cu) is the most precious metal present in a high amount (97.663 mg/g). Copper (Cu) is the most abundant metal present in PCB (Shah et al.

Table 1 Elemental composition of printed circuit board

S. no	Elements	Concentration (mg/g)	After bioleaching (mg/g)
1	Al	2.907	0.918
2	Ca	1.384	0.623
3	Cu	97.663	28.83
4	Cd	0.211	0.098
5	Fe	18.309	10.39
6	Ni	1.231	0.838
7	Zn	3.226	0.716
8	Ag	25.8	11.09
9	Pb	18.262	10.365
10	Hg	17.56	9.43

2014). Usha et al. (2017) reported that the copper (Cu) is the most base metal present in a high amount (19.0 mg/l) in waste-discarded printed circuit board.

Screening and identification of heavy metal resistance actinobacteria

The cultural characteristics of five actinobacterial strains are shown in Table 2. Heavy metal-resistant property of actinobacterial strains was screened by adopting the dot plot assay method. The growth of actinobacterial strains on different concentrations of selected heavy metals is given in Table 3. The results showed that strain TN10 showed resistance to a maximum of 1500 ppm concentration of $FeSO_4$, $CuSO_4$, and $NiCl_3$. Actinobacterial genera notably *Streptomyces* sp. are widely distributed in heavy metal-contaminated soil and it showed high resistance to toxic heavy metals and used as a bio-sorbent in the removal of heavy metals from the pollutants). Previously, El Baz et al. (2015) isolated the heavy metal-resistant *Streptomyces* sp. for removal of copper and nickel from metal-polluted soil. Madden et al. (2013) have reported the isolation of actinobacteria from Paper Wasp (Hymenoptera:Vespidae:Polistinae) nests for antimicrobial application. However, this is the first attempt using actinobacteria from insect nest for bioleaching of heavy metals from PCB. For identification strain, TN10 showed the presence of both aerial and substrate mycelium with no fragmentation in microscopic observation, and showed good growth on ISP2 agar with powdery consistency (Additional file 1: Fig. S1). Physiological characteristics of strain TN10 are given in Additional file 1: Table S1. Potential actinobacterial strain TN10 subjected to amplification of partial 16S rRNA gene and the obtained sequence with the length of 1420 base pair was identified as Streptomyces species. The potential Streptomyces strain TN10 was submitted to NCBI Genbank and assigned the accession number MH021968. The

Table 2 Morphological characteristics of actinobacteria strains

S. no	Strain no	Cultural characteristics						
		Growth	Consistency	AMC	RSP	SP	AM	SM
1	TN 10	Good	Rough	White	Pale yellow	−	+	+
2	TN 5	Good	Powdery	White	Pale yellow	−	+	+
3	TN 2	Good	Leathery	Pale yellow/dirty	Brown	−	+	+
4	TN 14	Good	Rough	Yellowish gray	Orange	+	+	+
5	TN 8	Good	Leathery	Dirty white	Reddish brown	−	+	+

+, present; −, absent; AMC, aerial mass color; RSP, reverse side pigment; SP, soluble pigment; AM, aerial mycelium; SM, substrate mycelium

Table 3 Screening of actinobacterial strains for metal resistant properties

S. no	Strain no	Concentration of ferrous sulfate $FeSO_4$ (ppm)				Concentration of copper sulfate $CuSO_4$ (ppm)				Concentration of nickel chloride $NiCL_3$ (ppm)			
		100	500	1000	1500	100	500	1000	1500	100	500	1000	1500
1	TN 10	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+
2	TN 5	+++	+++	+	−	+++	+++	+++	−	+++	+	+	−
3	TN 2	+++	+++	+	−	+++	+++	+	−	+++	++	+	−
4	TN 14	+++	+++	+++	−	+++	+++	+	−	+++	++	+	−
5	TN 8	+++	+	+	−	+++	+++	+++	−	+++	+++	++	+

+++, excellent growth; ++, good growth; +, moderate growth; −, no growth

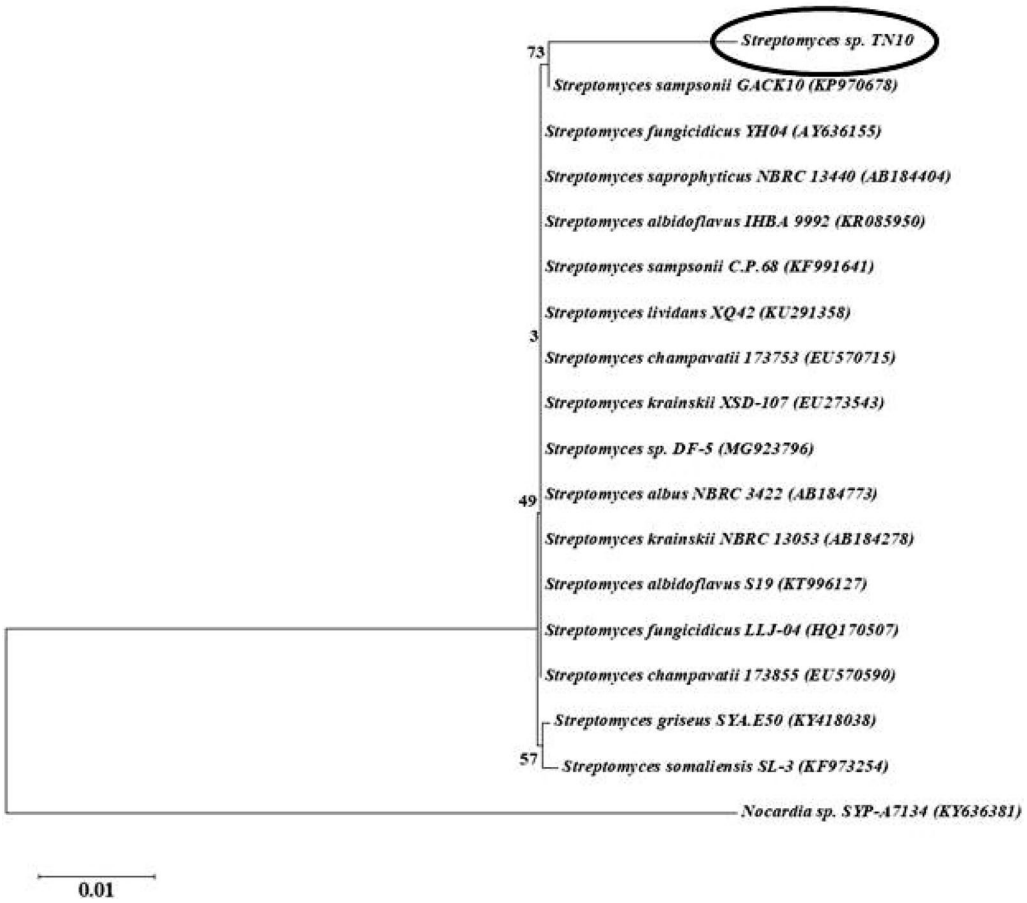

Fig. 1 The phylogenetic relationship of the potential actinobacterial strain TN10 based on 16S rRNA gene homology. The tree was constructed using the neighbor-joining method with pairwise-deletion model analyses, which were implemented in the molecular evolutionary genetics analysis (MEGA), version 6.0 program. The resultant tree topologies were evaluated by bootstrap analysis based on 1000 replicates. *Nocardia* sp. SYP-A7134 was used as out group

constructed phylogenetic tree clearly showed that strain TN10 is closely related to *Streptomyces albidoflavus* with the highest similarities (Fig. 1). Previously, several authors have reported the bioleaching potential of *Streptomyces* sp. isolated from different ecosystem ex (Brzezinskaa et al. 2013; Long et al. 2018; Daboor et al. 2014; El Baz et al. 2015). However, no previous evidence has been reported on bioleaching of heavy metals in printed circuit boards by *Streptomyces albidoflavus.*

Bioleaching of heavy metals from PCB

Heavy metals present in PCB were bioleached by adopting the shake flask method. Actinobacterial strain TN 10 showed the good growth in pH 5, 6 and 7. The maximum metal recovery were observed at pH 6 with zinc (Zn) in maximum 82.42 ± 1.32% in 72 h of incubation period followed by nickel (Ni) 81.23 ± 0.45% and least recovery was shown in Fe 42.60 ± 1.7% (Fig. 2b). The percentage of metal recovery was decreased in pH 5 and 7 (Fig. 2a, c). Similar findings were reported by Jadhav et al. (2016) that the maximum level of zinc extraction is 98% by *Aspergillus niger* supernatant with 0.1 M of NaOH. Chen and Huang (2014) reported recovery of copper 65% and nickel 100% in PCB wastewater sludge by *S. thermosulfidooxidans.* Previously, several studies have identified many fungal or bacterial strains with the capability to leaching heavy metals from PCB. The comparison of bioleaching potential of *Streptomyces* sp. TN10 with some of the previous studies shows that the strain TN10 has the capability of recovering higher concentration of heavy metals than most of the previously published microorganisms (Table 4).

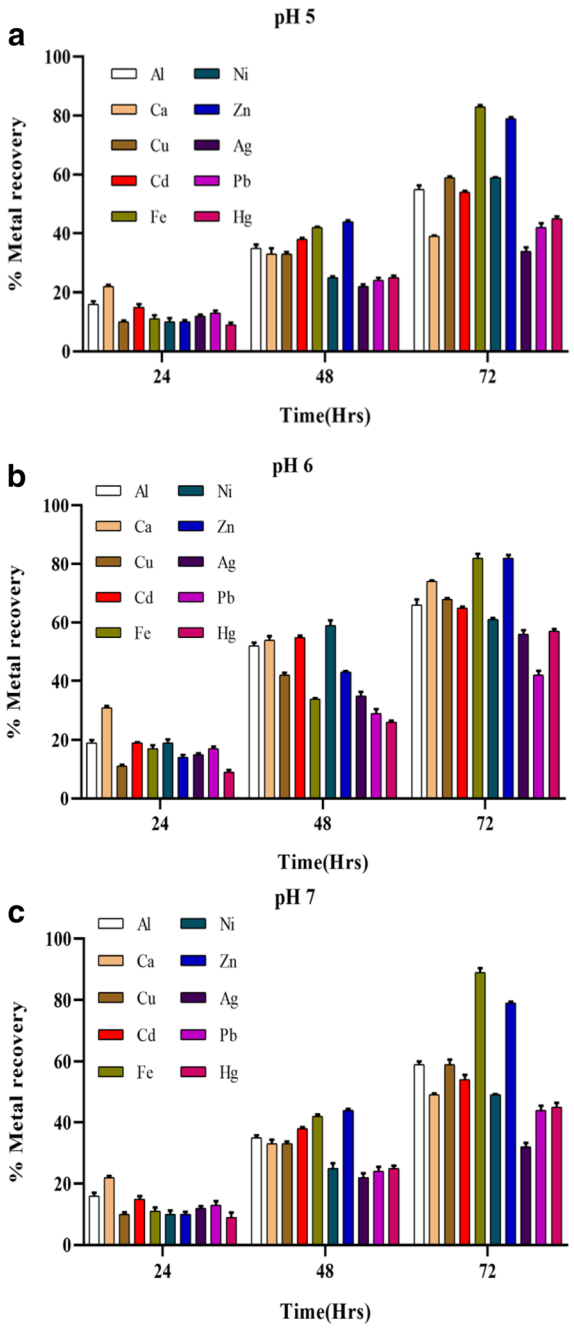

Fig. 2 Bioleaching of heavy metals from PCB (**a** pH 5, **b** pH 6, **c** pH 7)

Characterization of PCB and bioleaching residue

SEM analysis of PCB and bioleaching residue

Scanning electron microscope (QUANTA 200) was used to determine the structural morphology of raw PCB and bioleaching residue. The SEM image of PCB were showed in Fig. 3a which denotes the crystalline rod structures and spherical with a rough surface. After bioleaching, heavy metals present in the PCB were changed to granular shape with smooth surface (Fig. 3b). This structural change confirms that heavy metals in the printed circuit board were bioleached by *Streptomyces* sp. Previously Zhao et al. (2008) observed the structural changes in the PCB after the bioleaching has been identified by scanning electron microscope analysis.

XRD analysis

XRD is the foremost technique used for detecting the elements present in the sample. XRD results of PCB powder have unveiled five different peaks 22.33, 34.23, 40.45, 44.55, 66.81 corresponding to (581), (491), (464), (438) and (381) (Fig. 4a); whereas, our bioleaching residue unveiled seven values 22.19, 31.88, 45.51, 56.73, 66.39, 75.45, 81.20 with corresponding peaks (684), (783), (592), (442), (391), (393) and (361) both are having many similarities (Fig. 4b). Based on the peak size, the sizes of the metal are detected from 0 to 380 2-h peak. The peak from 31.88 to 75.45 denotes the presence of Ag and Hg. The present findings of the analysis were similarly reported by Das et al. (2009).

FT-IR spectra of bioleaching residue and PCB powder

The FTIR spectrum of e-waste (printed circuit board and bioleaching residue) is represented in (Fig. 5). The broad absorption peak of PCB powder around 3382 cm^{-1} is related to O–H stretching vibration band but after the bioleaching residue, there is a broad adsorption shift in a peak at 3409 cm^{-1} at the same stretching and the next 2924 cm^{-1} peak proves the existence of C-H stretching vibration both in PCB and bioleaching residue. Furthermore, (1612, 1094, 2307, 1640 cm^{-1}) peak attributes to the presence of C=O C=C/CN and RCO–OH stretching vibration. The above findings from FT-IR spectrum confirmed that citric acid and oxalic acid are the main reason for the decreasing pH during bioleaching. The PCB powder exhibits the metal group due to CH2 rocking vibration at 895 cm^{-1} and the bioleached residue at 816 cm^{-1}. The peaks at 1464 and 1431 cm^{-1} are the deformation vibrations. The bioleaching residue has more skeletal vibration at 590, 446, 433, 411 cm^{-1} than the PCB powder at 419 cm^{-1}. The rocking vibration peak arises at 1031 cm^{-1} in the bioleaching residue. Finally, the peak at 617 cm^{-1} corresponds to C–H wagging vibrations. Previously, Willner (2012) and Narayanasamy et al. (2018) reported the similar results that organic acids are

Table 4 Bioleaching of heavy metals from printed circuit board by several microorganisms

S. no	Microorganisms used for bioleaching of heavy metals from PCB	Metals extraction (%)	References
1	*Leptospirillum ferriphilum* and *Sulfobacillus thermosulfdooxidans.*	Cu(100)	Wu et al. (2018)
2	Acidithiobacillus thiooxidans	Zn(69) Cu(9) Pb(3) Cd(99), Ni(53), Cr(13)	Karwowska et al. (2014)
3	*S. acidophilus*	Zn(100), Cu (65)	Chen and Huang (2014)
4	*Aspergillus niger*	Gold (Au)-56	Delira et al. (2019)
5	*Acidithiobacillus ferrooxidans*	Copper(Cu)-80	Choi et al. (2004)
6	*A. niger*	Cu (99), Mg (99), Ti (98), Mn (84), Zn (82), Sn (78), Ni (76), As (76), Sr (73), Cd (72), Co (72), Ag (72), Al (70), Si (70), Pb (65), B (63), Fe (61), Pd (40), Au (30)	Jadhav et al. (2016)
7	*Leptospirillum ferriphilum*	Cu (60.33), Zn(75.67), Ni(71.09)	Shah et al. (2014)
8	*Sulfobacillus thermosulfidooxidans*	Cu(80)	Rodrigues et al. (2015)
9	*A. thiooxidans*	Cu(100), Ni(92), Zn(89), Al(20)	Mrazikova et al. (2015)
10	*Sulfobacillus thermosulfidooxidans*	Ni(81), Cu(89), Al(79), Zn(83)	Ilyas et al. (2007)
11	*Shewanella* sp.	Cu and Ni (49)	Kim et al. (2018)
12	*Chromobacterium violaceum*	Au(70)	Li et al. (2015)
13	*Chromobacterium violaceum*	Cu(76), Au(69), Zn(46), Fe(9), Ag(7)	Pradhan and Kumar (2012)
14	Mixture of *chromobacterium violaceum* and *P. aeruginosa*	Cu(83), Au(73), Zn(49), Fe(9), Ag(7)	Pradhan and Kumar (2012)
15	*Acidithiobacillus ferrooxidans*	Ni(86)	Mrazikova et al. (2014)
16	*Acidithiobacillus thiooxidans*	Cu(60)	Mrazikova et al. (2013)
17	*Aspergillus niger* MXPE6	Cu(28), Au(83), Ni(14)	Madrigal-Arias et al. (2015)
18	*Chromobacterium violaceum*	Au (11.31) and Cu (24.6)	Brandl et al. (2008)
19	*Pseudomonas chlororaphis*	Au (8.2), Cu (52.3) and Ag (12.1)	Ruan et al. (2014)
20	*Acidithiobacillus ferrooxidans*	Cu (96.8), Zn (83.8), and Al (75.4)	Yanga et al. (2014)
21	*Chromobacterium violaceum*	Au (22.5)	Natarajan and Ting (2014)
22	*Sulfobacillus thermosulfidooxidans* and *Thermoplasma acidophilim*	Cu (86), Zn (80), Al (64) and Ni (74)	Ilyas et al. (2010)
23	*Acidiphilium acidophilum (ATCC 27807)*	Cu (3.6) and Ni (86)	Das (2010)
24	*Acidithiobacillus* sp. and *Leptospirillum* sp.	Cu and Ni (100)	Vestola et al. (2010)
25	*Acidithiobacillus thiooxidans*	Cu(98)	Hong and Valix (2014)
26	*Acidithiobacillus thiooxidans*	Cu(74)	Bas et al. (2013)
27	*Acidithiobacillus ferroxidans*	Cu(99)	Yang et al. (2009)
28	*Acidithiobacillus ferroxidans*	Cu(99)	Wang et al. (2009)
29	*Thiobacillus thiooxidans and Thiobacillus ferrooxidans*	Cu, Ni, Al and Zn(90)	Brandl et al. (2001)
30	*Aspergillus niger, Penicillium simplicissimum*	Cu and Sn by 65%, and Al, Ni, Pb, and Zn by more than 95%	Brandl et al. (2001)
31	*Pseudomonas balearica SAE1*	Au(73) and Ag(41.6)	Kumar et al. (2018)
32	*Acidithiobacillus ferrooxidans*	Cu(100), Ni(90) and Zn(65)	Gorecka et al. (2019)
33	*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*	Cu(81), Pb(69) and Ni(61)	Lin et al. (2010)
34	*Acidithiobacillus ferrooxidans*	Cu(90.15)	Weihua et al. (2014)
35	*Sulfobacillus thermosulfidoooxidans*	Cu(89), Ni(81), and Zn(83)	Ilyas et al. (2007)
36	*Gallionella* sp. and *leptospiullam* sp.	Cu(95)	Oguchi et al. (2012)
37	*Acidithiobacillus thiooxidans, Thiobacillus* sp., *Bacillus subtilis and Bacillus cerus*	Cu(53), Ni(48.5) and Zn(48)	Karwowska et al. (2014)
38	*Sulfobacillus thermosulfidoooxidans*	Cu(95), Al(91) and Zn(96)	Ilyas et al. (2013)
39	*Acidithiobacillus ferrooxidans*	Cu(97), Al(75) and Zn(84)	Sun et al. (2017)
40	*Streptomyces albidoflavus TN10*	Al (66), Ca (74), Cu (68), Cd (65), Fe (42), Ni (81), Zn (82), Ag (56), Pb (46), Hg(59)	This study

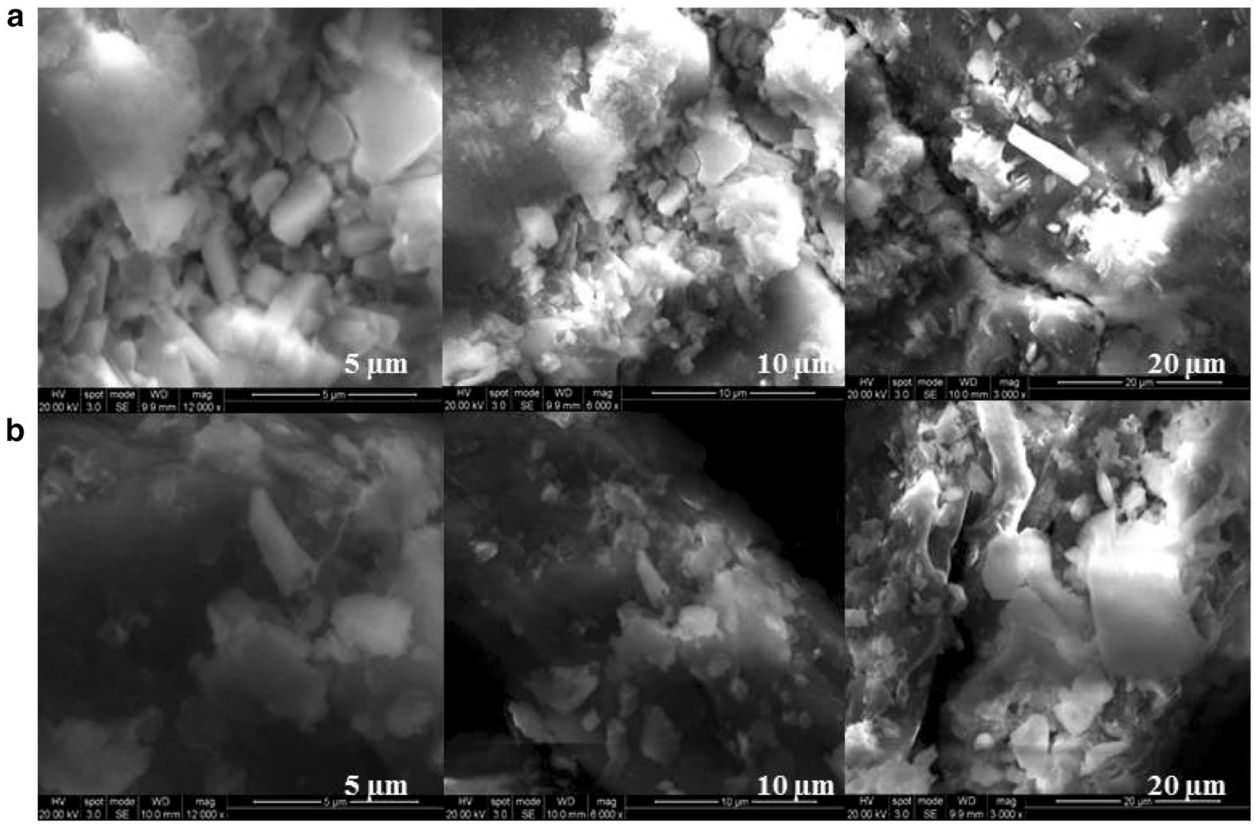

Fig. 3 Scanning electron microscope images **a** raw PCB, **b** bioleaching residue

possible reason for reduction of pH during bioleaching process.

Conclusion

The findings of the current study revealed that pH plays an important role in metal recovery using actinobacterial strain. The quantities of metal concentration were decreased from initial concentration because of the detoxification process by actinobacterial strain TN10. PCB and Bioleaching residues were characterized by SEM, FTIR and XRD. The results from this study provide the importance of metals recovery from the e-waste (PCBs) and using actinobacteria in bioleaching. From our study, we concluded that the actinobacterium *Streptomyces albidoflavus* TN10 can be used as an alternative biological candidate for the removal of metals from discarded PCBs with both economic and environmental perspectives.

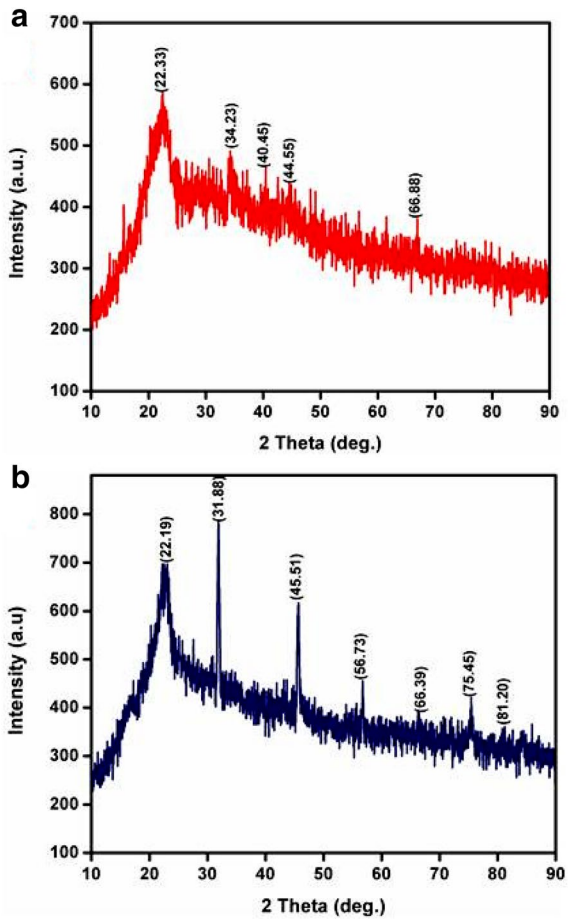

Fig. 4 XRD spectrum **a** raw PCB, **b** bioleaching residue

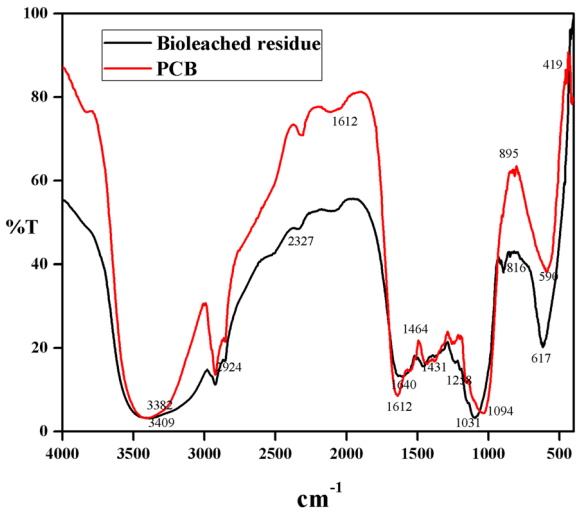

Fig. 5 FTIR spectrum of PCB and bioleaching residue

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40643-019-0283-3.

Additional file 1: Figure S1. Colony and micromorphology of actinobacterial strain TN10. **Table S1.** Physiological characteristics of potential actinobacterial strain TN10.

Abbreviations

PCB: printed circuit board; ICP-MS: inductively coupled plasma mass spectrometry; ISP: International Streptomyces Project; SEM: scanning electron microscope; XRD: X-ray powder diffraction; JCPDS: Joint Committee Powder diffraction Standards; FTIR: Fourier-transform infrared spectroscopy; Cu: copper; Al: aluminum; Sn: tin; Pb: lead; B: boron; Fe: iron; Si: silicon; Mg: magnesium; Ti: titanium; Ni: nickel; Sr: strontium; Zn: zinc; As: arsenic; Mn: manganese; Co: cobalt; Cd: cadmium; Pd: palladium; Au: gold; Ag: silver.

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Authors' contributions

DK, MR designed the experiment; VA, MK wrote the manuscript; ARA and JJ conducted the experiment; ST interpreted the result; VG and RM corrected. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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