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Technical Note
Feasibility of cyanide elimination using plants

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ABSTRACT

Cyanide is the reagent of choice for gold and silver extraction, but also a toxic chemical that may cause severe environmental pollution problems. Vascular plants possess an enzyme system that detoxifies cyanide by converting it to the amino acid asparagine. The phytotoxicity of cyanide is indirectly connected to the efficiency of this enzyme system: Plants only survive cyanide exposure up to a dosage they can metabolize. Cyanide phyto-toxicity was measured for the subtropical grass *Sorghum bicolor*. Potassium cyanide was not toxic when added to the irrigation water at up to 125mg KCN/l (50mg CN/l). In a degradation test, cyanide was efficiently degraded by sorghum roots and leaves. Cyanide elimination using plants seems to be a feasible option for gold and silver mine waste and wastewater. Theoretical estimates indicate that a large area of land is needed. But the process is cost effective, sustainable, and has less critical emissions than any competing technology. Until now, phytotreatment of gold mining wastewater has only been tested on a lab scale. With the current knowledge, a pilot-scale demonstration could be implemented immediately. © 2003 SDU. All rights reserved.

Keywords: Cyanide; Elimination; Mining; Gold; Silver; Mine effluents; Heavy metals; Phytotreatment; Plants; Sorghum; Phytotoxicity

1. INTRODUCTION

Cyanide (CN^-) is the leaching reagent of choice for gold and silver. The chemistry of the cyanide leaching technique was first published by G. Bödländer 1896. It is described by the reaction (Hollemann-Wiberg, 1976)

$$2 \text{ Au} + 4 \text{ NaCN} + \tfrac{1}{2} \text{ O}_2 \text{ --> } 2 \text{ Na[Au(CN)}^-] + 2 \text{ NaOH} \tag{1}$$
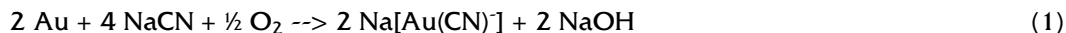
Gold dissolves as negatively charged complex. The same reaction occurs with silver. In gold and silver mining, a diluted sodium cyanide solution (0.05%) is sprayed on gold-containing crushed ore that is placed in large open air piles, commonly called heaps. The cyanide readily forms a water-soluble complex with the gold from which the gold can be recovered.

Since its commercial introduction in New Zealand over a century ago, cyanide has been used worldwide in the extraction of gold and silver. Although chemical replacements for cyanide have been investigated for decades, it remains the exclusive leaching reagent of choice due to a combination of availability, effectiveness and economics. This technique to leach silver and gold from low-grade ores and old mining wastes has been increasingly used since the 1980s. In the US alone, more than 150 heap-leach operations were active in the 1990s (Pipkin and Trent, 1997). Currently, there are about 875 gold and silver operations throughout the world, of which about 460 utilize cyanide. Up to 90% of gold is produced this way using 347 000 tons of sodium cyanide per year (Akcil, 2001). However, the cyanide heap leach process has been criticized by scientists and NGOs as a non-sustainable, environmentally damaging technique (Korte, 2000, 2001; FIAN, 2001; Mineral Policy Center, 2001).

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2. METABOLISM OF CYANIDE IN PLANTS

Several plant metabolic reactions involve cyanide. E.g., during ethylene synthesis in mature tissue, hydrogen cyanide is formed as a by-product (Manning, 1988). Consequently, plants have evolved effective detoxifying strategies for cyanide. The detoxifying enzyme system (beta-cyanoalanine synthase) connects free cyanide and cysteine to cyanoalanine. The final metabolite is asparagine, a non-toxic essential amino acid (Manning, 1988).

The phytotoxicity of potassium cyanide to basket willows (*Salix viminalis*) has been determined with the tree transpiration test (Trapp *et al.*, 2001; Trapp and Christiansen, 2003). The EC_{10} for t = 72h was 0.76mg KCN (0.3mg CN) per liter, the EC_{50} was 4.47mg/l. 5mg/l KCN were lethal after 3 weeks. Balsam poplars (*Populus trichocarpa*) could survive up to 2500mg/l ferroferricyanid (Prussian blue), although with reduced growth. Willows survived in gas work soils containing up to 452mg/kg total CN.

In the presence of living willows (*Salix alba*) and light, free cyanide was almost completely eliminated from the nutrient solution. This occurred also with a willow cell suspension (> 99%) and even by a dried-out stem (>80%) within one day (Trapp *et al.*, 2001a; Trapp and Christiansen, 2003). Volatilization and the formation of complexed cyanide were of minor relevance with respect to the elimination of free CN.

The *in vivo* capacity of woody plants, such as willow (*Salix viminalis, Salix viminalis x schwerinii*), poplar (*Populus trichocarpa*), elder (*Sambucus nigra*), rose (*Rosa rosa* var. Nordisk forever), birch (*Betula prubescens*) to remove cyanide was evaluated in tests with detached leaves and roots in potassium cyanide solutions of different concentrations (Trapp *et al.*, 2002). The highest removal capacity was obtained for basket willow hybrids (*Salix viminalis x schwerinii*). The *Michaelis-Menten* kinetics was determined. Realistic values of the half-saturation constant K_M were around 1.5mg CN/l; the maximum metabolic capacity v_{max} was between 9.3 and 14.5mg CN per kg plant fresh weight and hour.

The removal efficiency of willows was verified with a toxicity test using willow cuttings growing in hydroponic solution or sand. The willows in sand survived 423.5 hours irrigation with 50mg potassium cyanide (KCN) per liter solution (20mg CN/l). Willows in sand irrigated with 125mg KCN/l (50mg CN/l) died within a few days, as did willows grown in hydroponic solution with 50mg KCN/l (20mg CN/l). The roots of the surviving willows were able to consume 10mg CN per kg fresh weight and hour, which corresponds to the v_{max} found before. A maximum amount of 1000kg of free cyanide could be removed by willows per hectare and growing period (200d).

3. MATERIALS AND METHODS

Four tests were done to evaluate the feasibility of cyanide elimination using sorghum (*Sorghum bicolor*): an outdoor growth test with KCN in the irrigation water; an indoor toxicity test with KCN in the irrigation water; a laboratory test to measure volatilisation of HCN from pots planted with sorghum; and an *in vivo* elimination test in closed flasks with sorghum tissue.

3.1. Cyanide Solutions

Potassium cyanide solutions with 20mg CN/l (50mg KCN/l) and 50mg CN/l (125mg KCN/l) were prepared in the laboratory from a 0.05mol/l (0.34%) solution of KCN. As control, tap water was used. The pH of the solution was adjusted to above 8.5 with sodium hydroxide.

3.1.1. Outdoor growth test

The outdoor growth test with sorghum (*Sorghum bicolor*) was conducted in the period between 1/5/02 and 03/08/02 outdoors in Lyngby, Denmark. Sorghum seeds were sewn in a rectangular plastic container measuring 60cm (length) × 16cm (width) × 14cm (depth). The container was filled with sand taken from the University Campus (DTU) and topped up with

garden soil before sewing. The thickness of the sand and the soil top layer were 8cm and 5cm, respectively. The rectangular container was divided into five compartments with square shaped plastic plates, which fit well in the container, in order to keep individual compartment separated. Each compartment had about 15 to 20 sorghum plants. Plants were grown to a height between 25 to 30cm in a climatized growth chamber (26°C) until the end of the month of May and then moved outside. The plants were sheltered from rain using acrylic glass. Each compartment was watered with 80ml of the respective solution every morning for 60 days (from 03/06/02 to 03/08/02). Within that period, the weather was mainly warm and sunny, average temperature during the night was at or above 17°C, and during the day about 25°C most of the time.

3.1.2. Indoor toxicity test

The same cyanide solutions were used for the indoor toxicity test. Sorghum plants were grown indoors in 1000ml glass vessels placed under three 150W halogen lamps. All the flasks including the blanks were wrapped with alu-foil leaving small holes at the top for the grass. Weight measurements were recorded each morning, and transpired water was replaced. The transpiration was used as a measure for toxicity (Trapp *et al.*, 2000).

3.1.3. Indoor volatilization test

In this test, conditions were similar as before, but the sorghum plants were grown in a closed 9.5L desiccator. Pressurized cyanide-free air streamed through the vessel, and cyanide was trapped in 1 molar NaOH at the outlet. The gas stream was measured with the water replacement method at the end of the three days experiment. Cyanide solution was only added once.

At the end a mass balance on cyanide was performed. The concentration of free, easily liberatable, complexed and total cyanides in solution, soil and plant material was determined by the draft standard method ISO/DIS 11262 (ISO/DIS, 1999). Results were expressed as mg CN/l. Note that 1mg KCN equals 0.4mg CN.

3.1.4. *In Vivo* cyanide removal capacity of sorghum

The test system was made up of 27 250ml Erlenmeyer flasks filled with 200ml of 5mg CN/l, or 1mg CN/l, or distilled water (control). The pH of the solution was adjusted above 8.5 with sodium hydroxide. Two gram of leaves or roots were cut from 1 month old sorghum plants and placed in the flasks. The whole system was positioned near a window. The mean temperature and humidity of the test environment were measured as 22 ± 2°C and $65\pm5\%$ respectively. Aliquots of 0.8ml and 4ml were taken from the 5mg CN/l and 1mg CN/l flasks, respectively, for photometric analysis. The degradation test lasted for 8 days.

3.2 Results of the sorghum tests

3.2.1. Outdoor growth test

Cyanide solutions of 0, 20 and 50mg CN/l fed 60 days to the sorghum revealed no signs of toxicity. The leaves and stems appeared healthy and showed no signs of being poisoned. There was only some rusty coloration, probably fungal attack, on all leaves including the controls. After 1 month, the sorghum plants exposed to the highest CN dose had developed the largest shoots, but the smallest roots (Table 1). After 60 days, the plants were harvested, and roots, shoots and soil were analyzed for easy liberatable and complex cyanide (the sum of both is total cyanide). Cyanide levels in soil, roots and shoots were elevated in the compartments irrigated with 20 and 50mg CN/l. But only about 1% of the added cyanide was recovered (Table 2).

Table 1
Average growth of the outdoor sorghum plants from 3rd June to 3rd of August

Replicate	Exposure (mg CN/l)	Shoot mass (g)	Root mass roots (g)	Initial height (cm)	Final height (cm)	Growth (cm)
1	50	42.4	25.0	28	76	48
2	50	52.2	35.8	28	80	52
3	20	37.2	35.8	28	73	45
4	20	27.4	28.3	28	79	51
5	0	45.2	45.4	28	75	47

Table 2
Cyanide mass balance for the outdoor exposure experiment. EL = easy liberatable, C = complexed CN

Dose (mg CN/l)	Cyanide species	CN added (mg CN)	Conc. soil mg CN/kg	Mass in soil (mg CN)	Conc. roots (mg CN/kg)	Mass in roots (mg CN)	Conc. in shoots (mg CN)	Mass in shoots (mg CN)
0	EL CN	0	0.18	0.16	0.15	0.031	0.70	0.03
0	C CN	0	0.12	0.11	0.41	0.029	0.58	0.03
0	Total	0	0.30	0.27	0.56	0.061	1.28	0.06
20	EL CN	80	0.95	0.37	1.3	0.029	0.85	0.045
20	C CN	0	0.36	0.32	1.1	0.043	1.26	0.037
20	Total	80	1.31	0.69	2.4	0.072	2.1	0.083
50	EL CN	200	0.81	0.20	0.55	0.09	1.8	0.02
50	C CN	0	0.44	0.45	1.18	0.08	1.7	0.03
50	Total	200	1.25	0.66	1.73	0.17	3.5	0.05

3.2.2. Indoor Toxicity Test

Steady growth of sorghum was observed in all replicates of each concentration (0mg CN/l, 20mg CN/l, and 50mg CN/l). Leaves and stems looked green, healthy and showed no signs of being poisoned. This is supported by the fact that the average heights of the grass in each flask increased by at least 15cm/week. The daily average transpiration increased consistently. Observation showed that the soils in the sorghum containing flasks were significantly drier than in sorghum free controls. Average growth was slightly increased for the 20 and 50mg CN/l fed sorghum plants, compared to controls (Table 3).

Table 3
Average growth of the indoor sorghum plants (in parenthesis: standard deviation)

Dose (mg CN/l)	Shoots (g)	Roots (g)	Initial height (cm)	Final height (cm)	Growth (cm)
0	19.6 (3.85)	4.1 (0.31)	33.7 (0.58)	70.0 (2.0)	36.3 (1.5)
20	18.9 (4.81)	5.2 (0.42)	33.0 (1.0)	72.0 (7.2)	39.0 (6.2)
50	20.5 (2.56)	5.0 (0.94)	33.0 (1.0)	73.3 (9.9)	40.3 (9.0)

The better growth of the cyanide exposed sorghum, compared to the controls, might be due to cyanide being used as a nitrogen source. Toxic levels of cyanide exposure could not be established, because it was decided to avoid higher cyanide concentration (students work). One thing is however certain, and that is sorghum (*sorghum bicolor*) has the ability to tolerate high concentrations of cyanide (125mg KCN/l) and continues to grow very well.

Figure 1 shows the transpiration of the sorghum plants, related to the initial transpiration. In all experiments, the transpiration increased quickly, and fastest at the highest dose. After approx. 260 hours, the plants had reached the lamps, and the position of the lamps and the plants had to be changed. This explains the sharp decrease after this period.
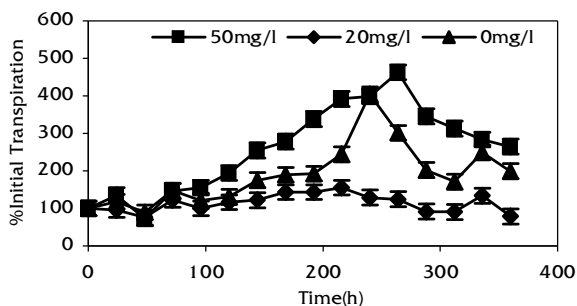
Figure 1. Transpiration of sorghum irrigated with 0, 20 and 50mg CN/l, related to the initial transpiration

Table 4 shows the mass balance for the indoor exposure experiment. As in the outdoors experiment, concentrations in soil, roots and leaves of the flasks irrigated with cyanide solution were elevated. Concentrations in roots were higher than in shoots. Only a few % of the applied cyanide could be recovered.

Table 4
Cyanide mass balance for the indoor exposure experiment. EL = easy liberatable, C = complexed CN

Dose (mg CN/l)	Cyanide species	CN added (mg CN)	Conc. Soil (mg CN/kg)	Mass in soil (mg CN)	Conc. roots (mg CN/kg)	Mass in roots (mg CN)	Conc. in shoots (mg CN)	Mass in shoots (mg CN)
0	EL CN	0	0.11	0.10	0.18	< 0.001	0.03	< 0.001
0	C CN	0	0.12	0.10	0.15	< 0.001	0.04	< 0.001
0	Total	0	0.23	0.20	0.33	<0.002	0.07	< 0.002
20	EL CN	15.2	0.26	0.21	4.0	0.02	2.8	0.05
20	C CN	0	0.24	0.19	9.6	0.05	3.0	0.05
20	Total	15.2	0.50	0.40	13.6	0.07	5.8	0.1
50	EL CN	38	0.24	0.17	3.4	0.02	2.2	0.05
50	C CN	0	0.17	0.12	6.8	0.03	4.1	0.08
50	Total	38	0.41	0.29	10.1	0.05	6.3	0.13

3.2.3. Indoor volatilization experiment

In this experiment, the focus was on loss via gas phase. Soil and sorghum were not analyzed. The conditions were comparable to the indoor experiment II. The gas stream was 1.0L/min in the inflow ($1.44m^3$/d) and 0.6L/min in the outflow. The results were corrected for this loss. The trapping efficiency of cyanide from the gas into the NaOH solution had been determined recently at 92% to 98% (Trapp *et al.*, 2001a, 2002). Initial evaporation of cyanide was high, but at day 2 and 3, evaporation was negligible (Table 5). In total, 18.9% volatilized from the soil irrigated with 20mg CN/l, and 5.0% from the soil with 50mg CN/l. The reason for the difference is not known. The average concentration in the gas space of the desiccator during day 1 was 0.52 and $0.35mg/m^3$ (Table 6). This is far below the allowed work place standard in Germany ($11mg/m^3$). However, initially there may have been higher air concentrations. The equilibrium partitioning coefficient air to water (dimensionless Henry's Law constant) is 0.00158. This means that theoretical maximum concentrations (chemical equilibrium) are $79mg/m^3$ and $32mg/m^3$ for the 50mg CN/l and the 20mg CN/l experiment, respectively.

Table 5
Amount of cyanide trapped in the NaOH gas trap

Experiment	Day 1 mg CN	Day 2 mg CN	Day 3 mg CN	Added mg CN	volatilized %
20mg CN/l	0.75	0.003	0.001	4.0	18.85
50mg CN/l	0.50	0.002	0.001	10.0	5.03

Table 6
Concentration of cyanide in the gas space of the desiccator (mg CN/m^3)

Experiment	Day 1	Day 2	Day 3
20mg CN/l	0.52	0.002	< 0.001
50mg CN/l	0.35	0.0014	< 0.001

3.2.4. *In Vivo* cyanide removal capacity of sorghum

The ability of sorghum leaves to eliminate cyanide from solution is obvious from the degradation experiment (Figures 2, 3). In the test with 1mg CN/l, about 98.5% of cyanide was eliminated after 24h. The removal capacity of sorghum leaves was between 3.14mg CN/h.kg leaves and 3.5mg CN/h.kg leaves. The removal of cyanide in the 5mg CN/l solution took considerably more time. Probably, the cyanide killed the plant after a while. The initial removal rate at 5mg CN/l was between 3.96mg CN/h.kg leaves and 4.68mg CN/h.kg leaves.

The removal of cyanide by roots was smaller in the 1mg CN/l solution, compared to the leaves (Figures 2, 3). The removal capacity of roots was about 2.8mg CN/h.kg root. The removal capacity of roots at 5mg CN/l was higher than for leaves in the range of 4.5mg CN/h.kg plant to 6.94mg CN/h.kg plant. The cyanide in the controls without plants (blanks) remained almost constant.
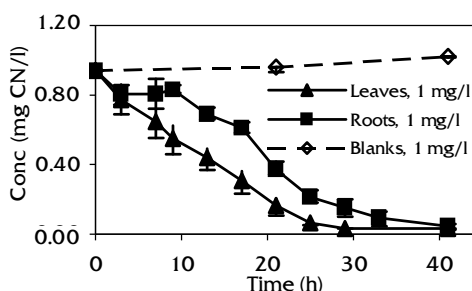

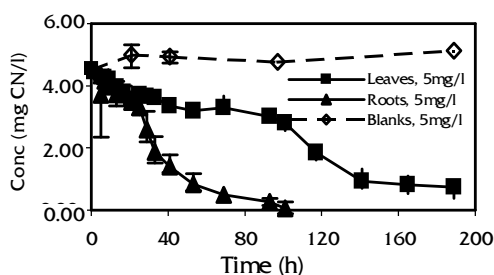Figure 2. Removal of cyanide by sorghum (leaves & roots) from 1mg CN/l solution

Figure 3. Removal of cyanide by sorghum (leaves & roots) from 5mg CN/l solution

4. CONCEPT FOR DETOXIFICATION OF CYANIDE BY PLANTS

The fact that plants can remove high amounts of cyanide might be applicable to the elimination of cyanides in waste and wastewater, e.g., from gold mining. This could be realized by constructed wetlands or artificial ponds with aquatic plants, if the concentration is low, or by areas of land planted with selected crops or trees and irrigated with cyanide containing wastewater (at higher concentrations). Figure 4 shows the principles of the system.

The cyanide needs to be well dosed: overdose damages the plants irreversibly. Appropriate amounts act as nitrogen fertilizer, because asparagine is produced. The concentration of cyanide in the water does not determine the toxicity, as the chemical is almost instantaneously metabolized inside plant cells. It is the dosage of CN (the amount taken up by the roots) that determines the effect. High concentrations must slowly be added to the root zone, *e.g.*, through

a sandy soil, with moderate hydraulic conductivity. Lower concentrations can be directly applied to plants in constructed wetlands.
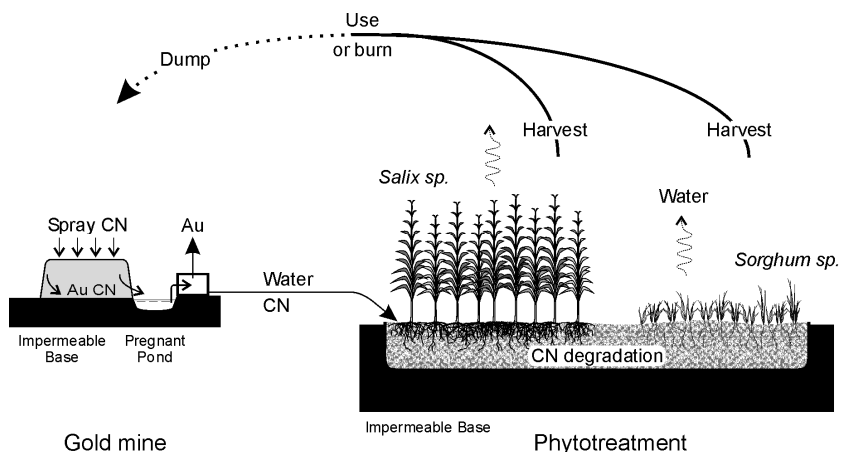

Figure 4. Principles of the phytotreatment of cyanide-contaminated mining wastewater

4.1. Plant Selection

The selection of plants depends on the conditions at the mine (climate, soil). Easy laboratory tests can determine the catabolic capacity of the species and the tolerated dose of cyanide. Basket willow (*Salix viminalis* hybrid), which had the fastest removal capacity of the tested Danish woody plants, has been domesticated for centuries and grows all over Europe, Northern Africa, Asia including the Middle East, Mexico and South America, but more in the humid and temperate regions (Richter and Dallwitz, 2002). Basket willow is adapted to very good water supply, and therefore cannot be used in dry regions. The most important gold producer of the world, however, is South Africa, followed by the USA. Other important gold producers are also located in subtropical or tropical regions, *e.g.*, Ghana or Turkey. Sorghum (*Sorghum bicolor*) stems from equatorial Africa and is cultivated in all subtropical and tropical countries, including Southern USA (Franke, 1989). Sorghum is resistant against drought and bad soil conditions, but does not grow below daily average temperatures of 17°C.

4.2. Sample calculation

Based on the aforementioned degradation rate of 1000kg CN per year and hectare, an example calculation for the Küçükdere gold mine project of the Tüprag Metal Mining Ltd. near the bay of Edremit, Turkey, follows. The data were published in an experts' statement by F. Korte (http://www.infu.uni-dortmund.de/korte-goldmining/Expert.html). For processing 250 000 tons of ore per year with 3mg/kg gold, 365 000m^3 of process water are needed and 125t of sodium cyanide (66.3t CN) are used (0.5kg NaCN/t ore or 0.2kg CN/m^3 water). 750kg of gold are recovered.

4.2.1. Willow plantation

If 66 300kg cyanide per year are treated by a willow plantation with a removal capacity of 1 ton CN/ha.year (= 1.88 tons NaCN/ha.year), an area of 67 hectares of plantation is needed. If it is assumed that - due to the milder climate in Turkey - the growing season is year-round instead of 200 days, this area reduces to 37 hectares. This figure still neglects any natural attenuation processes. Under favorable conditions, the area needed is smaller.

The costs for constructing 1 ha of willow, as evaluated for the Sørup waste site (Denmark) by Kåre Press-Kristensen, County of Copenhagen (2002) (Table 7), is US$7562.5, mainly for buying the trees. For 37ha, the costs are US$279 812 (€302 000). If the gold mine runs for 6 years,

that is US$46635.3 per year, or US$0.70 per kg CN (€0.76 per kg CN). The costs are lower for longer operation times, because the main costs are for establishing the plantation.

In normal agricultural practice, costs of planting and harvesting plants are balanced by the value of the harvested product. The price for one cubic meter wood chips for firing is currently low, in Germany about €15/m^3 (BR 2002). With approx. 10 tons/(ha year) wood production (Sitte *et al.*, 1991), an additional income of €5550 (US$5141) per year is gained from selling or firing the harvest product.

Table 7
Projected costs for 1ha of willow forest at Sørup, Denmark (Press-Kristensen, 2002), and projected for Küçükdere, Turkey

Treatment	Costs € per ha	Costs Küçükdere € per 37ha and 6 years	Costs US$ per ha	Costs Küçükdere US$ per 37ha and 6 years
Preparing the site (melioration)	270	10 000	250	9 250
Planting willows	400	14 800	375	13 875
Buy trees	7421 (23 000 willows)	274 577 (851 000 willows)	6875 (23 000 willows)	254 375 (851 000 willows)
Transport costs	70	2 590	62.5	2 312.5
Sum	€8161	€302 000	€7562.5	€279 812

* 8 Danish Kroner = 1 US$; 7.411 Danish Kroner = 1 € (May 2002)

4.2.2. Sorghum fields

We cannot yet exactly quantify the cyanide removal capacity of sorghum. If we assume that, as with willows, 1.8 tons cyanide per year and ha can be treated, an area of 37ha is required. However, sorghum is an annual grass, and needs time to establish the required biomass. Therefore, at least two parallel fields are needed, which gives 74ha. The costs for sorghum production is not known to us (Denmark is no commercial producer), but the world market price for sorghum corn has been around US$100 per ton from 1982 to 1996 (Baltensperger, 1996). The global average production was 1.53 tons/ha, with up to 10 tons/ha under optimal conditions in the US (Franke, 1989). It is unlikely that the production costs are higher than the price, hence we assume maximum cost of US$150 to grow 1ha *Sorghum* (global average). For 74ha this gives US$11 100 costs per year.

4.2.3. Comparison to existing technology

Mosher and Figueroa (1996) compared the costs of existing treatment methods (Table 8). The two more common methods, the hydrogen peroxide oxidation and the INCO process, would have annual costs of US$431 000 and US$80 000, respectively, if used at the Küçükdere gold mine.

Table 8
Comparison of costs for cyanide removal

Name	Costs (US$ per kg CN)	Costs US$ Küçükdere (66.3t CN/year)	Costs (€ per kg CN)	Costs € Küçükdere (66.3t CN/year)
Alkaline chlorination	15.78	1 046 214	17.0	1 128 865
Hydrogen peroxide	6.51	431 613	7.0	465 710
INCO process	1.2	79 560	1.3	85 845
Biological oxidation	0.6	39 780	0.65	42 922
Willow plantation	0.70	46 635	0.76	50 333
Sorghum fields	0.17	11 100	0.18	11 874

From Table 8 can be seen, that the costs are lowest for the biological methods, with Sorghum fields beating all competing methods in the price. The price may be far too optimistic, because it

does not include the price for a wastewater distribution system, and operation costs. Operation costs are for monitoring cyanide concentration, adjusting pH, and possibly adding some nutrients. Also, barriers against infiltration into groundwater may be needed in areas with groundwater use, or due to legal restrictions. Also, the price for willow is for Denmark (a high-price country), and that for sorghum is global average. On the other hand, if the harvested sorghum corn can be used (e.g., as seeds for sewing), additional income is gained, probably higher than the assumed costs.

Most mining operations are in remote areas, so space should not be a major problem. The elimination by plants can also be used in combination with other cyanide elimination technologies. For example, the cyanide elimination with hydrogen peroxide is most effective to reduce concentrations from 200mg/l down to 20mg/l. Below this concentration, the H_2O_2 oxidation is less effective and more expensive (Norbert Steiner, Stockhausen, personal information).

The phytotreatment is also superior if the effluent composition is considered. The alkaline chlorination of cyanide leads to the production of cyanate (OCN^-), while chlorinated products and free chlorine may be emitted. The oxidation of cyanide with H_2O_2 yields cyanate or nitrate (NO_3^-), both less toxic than cyanide, but nevertheless undesired compounds in a watershed (Mosher and Figuero, 1996). The INCO process does not treat thiocyanate and ferrocyanides, and cyanate is formed (David Menne, personal communication). The bacterial breakdown of cyanide yields ammonium (NH_4^+), a compound that is rather toxic to fish, and may induce eutrophication of lakes and ponds. Combined anaerobic and aerobic treatment removes ammonium but releases nitrate (Akcil and Mudder, 2003). The plantations or fields for the treatment of mining wastewater may be designed in a way that all wastewater is consumed and transpired by the plants. This also means "zero emissions" (except with the harvested product).

5. CONCLUSIONS

The treatment of gold mining wastewater by plants combines several benefits: Cyanide is detoxified by the plant's enzyme systems, as long as the dosage is administered correctly; cyanide simultaneously acts as a fertilizer for plant production. Moreover, the plants remove heavy metals including gold and silver (Anderson *et al.*, 1998). Plants can be burned for energy production. If the gold or silver content is high, it may be recovered from the ash. If the heavy metal content in the ash is high, it may be necessary to treat the ash as toxic waste.

Environmental legislation associated with the land disposal of cyanidation tailings is becoming increasingly stringent worldwide (Akcil, 2001). Using plants to clean mining waste and wastewater is a sustainable and environmentally friendly green technique.

The proposed concept is at the moment based on laboratory experiments and needs confirmation by pilot-scale demonstration at a gold mine. With the current knowledge, such a demonstration can easily and immediately be implemented.

ACKNOWLEDGEMENTS

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