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REVIEW ARTICLE

Suitability of thermal plasma for solid waste treatment and non-thermal plasma for nano-scale high-tech plasmonic materials: a concise review

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Abstract
In the recent past, plasma waste technology has emerged to be an environmental friendly and beneficial technology. In this review, current status of thermal plasma, non-thermal plasma and its application for nano-scale high-tech plasmonic materials based on the scientific and technical comprehensive observation are included. Generally, thermal plasma is used for solid waste treatment but non-thermal plasma is being utilized for plasmonic materials. The current research incorporated in two phases: thermal plasma and non-thermal plasma. In the first phase, understanding and detailed information about plasma torches have been included such as DC transfer and non-transfer arc plasma torches. In addition, solid waste treatment, municipal waste, healthcare issue, steel making and treatment through plasma jet injection have been reviewed extensively. In the second phase, state-of-the-art review has been addressed for dielectric barrier discharge (DBD) and its utility for plasmonic materials. The analysis concluded that the thermal plasma is the optimal choice for treating solid waste issues and the application of non-thermal plasma such as DBD is the most useful and latest approach for plasmonic material. The prime objective of this review is not only to provide the comparison between thermal or non-thermal plasma but to recommend the ideal and most optimized suitable technique for solid waste treatment and bio-medical applications.

Keywords Thermal plasma · Non-thermal plasma · Solid waste · Health care · Plasmonic materials

Introduction

The state of matter having identical temperature value for both heavy particles and electrons characterized by high energy density is termed as 'thermal plasma' while a non-thermal plasma is obtained using less power which is characterized by an energetic electron temperature (Jiang et al. 2014). It is important to use the thermal plasma technologies for waste treatment and non-thermal for bio-medical issues. For this purpose, a comprehensive and detailed scientific literatures are presented in this review report supported by Table 1. There are certain ways from which it is possible to extract liquid wastes for example, drained oil from chemical and automobile industries; chemical solutions/solvents from industries; highly toxic waste fluids (PCBs) from mechanical/electronic factories; and depleted fluid such as halon and chlorofluorocarbons. While, solid waste has its origin from industrial wastes including toxic graded plastic, tires, petroleum by products; medical wastes derived from pharmaceutical industry and hospitals; waste from municipality; and conducting material wastes from electronic industries.

This review comprised of two sections, providing the thermal plasma treatment for solid waste and demonstrates the latest application of non-thermal plasmas. In the first section, plasma torches such as DC transfer arc plasma torches and DC non-transfer arc plasma torches are presented. In addition, plasma treatments for the processing of solid waste is discussed. In the second section, a newly developed method are discussed for plasmonic nano-material, which is an interesting material for diverse applications such as energy utilities, solar/fuel cells and sensor, solid, medical issues and laboratory equipment. Presently, number of novel methods are available for the treatment of plasma waste. In this review, we emphasize on the approaches which are practicing or under developing phase for solid waste and

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Table 1 Global analysis of solid waste through thermal and non-thermal plasma for nano-scale high-tech plasmonic materials

Non-thermal plasma (Wiegand et al. 2017; Chen and Wirz 2020; Domonkos et al. 2021; Kampf et al. 2020; Ollegott et al. 2020; Stryczewska 2020; Izadjoo et al. 2018; Laroussi 2018; Sarangapani et al. 2017a, b; Hertwig et al. 2017; Kim et al. 2011)

Main author (with ref.)	Description	Reference year
Wiegand et al. (2017)	Recent development and principles are discussed 1. Study about Cold atmospheric pressure plasmas (CAPPs) 2. Investigation of antimicrobial effect 3. Method: Plasma BLASTER MEF	2017
Chen and Wirz (2020)	Recent development and principles are discussed 1. Development of CAS devices 2. Implement to COVID-19 3. Advantages of sanitation and treatment	2020
Domonkos et al. (2021)	Research focused on following main points 1. Plasma treatment 2. Surface modification 3. Atmospheric pressure and low-temperature plasma 4. Plasma medicine and agriculture research 5. Pathogen inactivation investigation	2021
Kampf et al. (2020)	1. Address SARS-CoV-2 2. Describe human to human transmission process 3. Analysis: SARS, MERS, HCoV 4. Efficiently inactivated: 62–71% ethanol, 0.5% hydrogen peroxide 5. Less effective: 0.05–0.2% benzalkonium chloride	2020
Ollegott et al. (2020)	Recent development and principles are discussed 1. Investigate: non-thermal plasma, heterogeneous catalyst, chemical transformations, High densities of reactive species, presents several plasma-catalytic DBD applications	2020
Stryczewska (2020)	Review base on non-thermal plasma reactors (NTPR) 1. Dielectric barrier discharge (DBD) 2. Atmospheric pressure plasma jets (APPJ) 3. Gliding arc discharge (GAD)	2020
Izadjoo et al. (2018)	Detailed explanation about waste treatment through cold plasma 1. Describe the broad spectrum antimicrobial technology and causes of high incidence of infections 2. Increasing of wound healing by: monocyte stimulation, keratinocyte proliferation, cutaneous microcirculation 3. Dentist treatment through CAP 4. Aim to provide the therapeutic application of the cold plasma technology	2018
Laroussi (2018)	Review based on plasma medicine 1. Target: applications including wound healing and cancer treatment 2. Research expanded to: low-temperature plasma and biological cells and tissues	2018

Table 1 (continued)

Main author (with ref.)	Description	Reference year
Non-thermal plasma (Wiegand et al. 2017; Chen and Wirz 2020; Domonkos et al. 2021; Kampf et al. 2020; Ollegott et al. 2020; Stryczewska 2020; Izadjoo et al. 2018; Laroussi 2018; Sarangapani et al. 2017a, b; Hertwig et al. 2017; Kim et al. 2011)		
Sarangapani et al. (2017a)	Detailed explanation about waste treatment through cold plasma 1. Investigate the efficacy of cold plasma treatment 2. This is potential bio-decontamination technology and can be apply to food products 3. Efficiency: DBD, 50 Hz, 0–5 min, air, 80 kV, 80.18% for boscalid, 75.62% for Imidacloprid 4. Investigation: effective chemical decontamination of blueberries	2017
Hertwig et al. (2017)	Research focused on following main points 1. Investigation: cold atmospheric pressure plasma, ATCC BAA-1045 2. Efficiency: SDBD, 20 kV, 15 kHz, 15 min 3. Gases: air, N2, CO2 4. Result: browning of unpeeled almond surface color 5. Suggestion: pasteurization of almonds treatment through cold plasma is an alternative technology	2017
Sarangapani et al. (2017b)	1. Efficiency: radio frequency plasma, 13.56 MHz, 30 W to 50 W, 5 to 15 min 2. Pressure: 2 Pa and air with 0.15 mbar 3. Result: decrease the hardness, moisture and ash	2017
Kim et al. (2011)	1. Efficiency: atmospheric pressure plasma, 75–125 W, 13.56 MHz, 60–90 s 2. Gases: He, He + O_2 3. Results: pH has no change and L* comparatively increase	2011
Thermal plasma (Inaba and Iwao 2000; Chang 2001, 2008; Urashima and Chang 2000; Chang et al. 2005, 2008; Chu et al. 1998; Tzeng et al. 1998; Yantsis et al. 2008; Ching et al. 2001; Karpel Vel Leitner et al. 2005; Yamatake et al. 2006; Yuan et al. 2010; Hoornweg and Perinaz 2012; Margallo et al. 2014; Zhao et al. 2010; Carnogurska et al. 2015; Lazar et al. 2015; Pan et al. 2013; Pan and Xie 2014; Yi-Ming et al. 2012; Vu et al. 2012)		
Inaba and Iwao (2000)	Detailed explanation about waste treatment through DC discharge plasma 1. Solid waste 2. Low-level nuclear waste 3. Aluminum 4. Fly ash 5. Asbestos	2000
Chang (2001)	Recent development and principles are discussed 1. Plasma pollution control technology 2. Reactor technology 3. Material generated pollution	2001
Chang (2008)	Main focused on plasma pollution control and their limitation based on chemistry and physics knowledge	2008
Urashima and Chang (2000)	Recent development and principles are discussed 1. Gaseous pollution control technology 2. Reactor technology	2000

Table 1 (continued)

Main author (with ref.)	Description	Reference year
Non-thermal plasma (Wiegand et al. 2017; Chen and Wirz 2020; Domonkos et al. 2021; Kampf et al. 2020; Ollegott et al. 2020; Stryczewska 2020; Izadjoo et al. 2018; Laroussi 2018; Saranga-pani et al. 2017a, b; Hertwig et al. 2017; Kim et al. 2011)		
Chang et al. (2005)	The research execute three main focused 1. Ash volume reduction based on plasma torch 2. Comparison of three phase arc processes based on incineration source 3. Detailed explanation and comparison for solid product detoxicity	2005
Chu et al. (1998)	Research focused on following main points 1. Vitrified slag and their effectiveness of an indirect plasma heating 2. INER system 3. Monolithic metal nugget 4. Gravity effect	1998
Tzeng et al. (1998)	Research and development of non-transferred plasma torch 1. Introduce homemade non-transfer plasma torch 2. Power: 100 KW 3. Plasma furnace: 10 kg/h 4. Temperature: 1700 °C and 1650 °C 5. Obtained high quality for Glassy or ceramic slags 6. Achieved simulation results of radioactive wastes by plasma torch 7. Leaching indices are all greater than ROC regulated values	1998
Chang et al. (2008)	Development of electrohydraulic discharge systems 1. Treatment mechanisms 2. Treatment of chemical contaminants 3. PAED municipal sludge treatment	2008
Yantsis et al. (2008)	Author deal (PAED) plasma to prevent secondary contamination problems specifications 1. Used zooplankton species 2. Ranges of Daphnia magna (1.5–2.5 mm; mean length of 1.81 mm) 3. Treatment applied = 0.5 kJ/pulse PAED in a 3-L reactor	2008
Ching et al. (2001)	EHD (electrohydraulic discharges) has been studied with the specification of 5.5 kV and 90 KA	2001
Karpel Vel Leitner et al. 2005)	PAED (pulsed arc electrohydraulic discharge) system has been studied to find out aqueous solutions	2005
Yamatake. et al. (2006)	Two main focused on the research 1. Study of PAED (pulsed arc electrohydraulic discharge) system for eccentric electrode cylindrical reactor 2. Application of PBSW (phosphate-buffered saline water)	2006
Yuan et al. (2010)	Detailed explanation about waste treatment through DC discharge plasma 1. DC non-transferred arc plasma torch (DC water plasma)	2010
Hoornweg and Perinaz (2012)	Provide the extensive review of solid waste treatment (SWT)	2012

Table 1 (continued)

Main author (with ref.)	Description	Reference year
Non-thermal plasma (Wiegand et al. 2017; Chen and Wirz 2020; Domonkos et al. 2021; Kampf et al. 2020; Ollegott et al. 2020; Stryczewska 2020; Izadjoo et al. 2018; Laroussi 2018; Sarangapani et al. 2017a, b; Hertwig et al. 2017; Kim et al. 2011)		
Margallo et al. (2014)	Main focused of the research are 1. Bottom ash 2. Environmental management 3. Solid waste incineration 4. Life cycle assessment approach	2014
Zhao et al. (2010)	Recent development and principles are discussed regarding the issue of bottom ashes and medical waste incinerator	2010
Carnogurská, et al. (2015)	Research focused on MSW (municipal solid waste) fly ash treatment and application of plasma measurement	2015
Lazar et al. (2015)	Main focused of the research are 1. Obtained result for fly ash 2. Obtained result for high-temperature gasification of RDF 3. Incineration of municipal waste	2015
Pan et al. (2013)	Research and development of detoxifying PCDD/Fs, fly ash, medical waste incineration and DC double are plasma torch	2013
Pan and Xie (2014)	Detailed explanation of melting incinerator ashes and development of DC plasma torch	2014
Yi-Ming et al. (2012)	Main focused of the research are 1. Material research 2. Vitrification of municipal solid waste 3. Fly ash	2012
Vu et al. (2012)	Main focused of the research are 1. Bottom ash 2. Fly ash 3. Glass–ceramic	2012

bio-medical applications. In addition, it is aim to present basic principles and experimental procedure to identify the pros and cons of thermal or non-thermal plasma in view of solid waste treatment processes and bio-medical issues.

Concept of plasma

In nature, the fourth state of matter is termed as plasma which is a combination of electron, ions and neutral particles. Plasma can be generated by flowing a current through the gas and this electrical breakdown produces ions, excited species, atoms and photons (by the collision of charge carrier and the gas molecules) (Boulos et al. 1994). Plasma is an electrical conductor which is formed by number of gases such as argon, nitrogen hydrogen, steam, helium, air oxygen, CO, and CO_2 (Moustakas et al. 2005). Therefore, for plasma generation, we commonly select Argon and nitrogen gas (Mabrouk et al. 2012). Plasma's are classified in terms of atmospheric pressure and low pressure. These are types of plasma, which are characterized by pressure, temperature and electron densities. Thermal and non-thermal plasma are two groups of atmospheric pressure plasma as presented in Table 2. Thermal plasma can be formed by flames, electric sparks and atmospheric arcs. It described by proximate equality between neutrals, ions and electrons. Its application includes waste material treatment, municipal waste, material processing, microwave devices, plasma torches, process nuclear waste, medical waste, etc. In non-thermal plasma, ions thermal motion, pressure force and magnetic force are not considered. Instead, electric force is required to exert the particles. Some of the examples includes discharge of flow in fluorescent tubes and in earth ionosphere. Treatment of biological tissues and polymers are application of non-thermal plasma.

Table 2 Grouping of plasma types (Chen 1974; Chang 2006, 2009)

Plasma type	State	Example
Thermal plasma (quasi-equilibrium)	$T_{electron} \approx T_{ion} \approx T_{gas} \leq 10^4$ to 10^8 K nelements $\geq 10^{22}$ to 10^{28} m^{-3}	1. Solid and liquid waste treatments 2. Material processing 3. Microwave devices 4. Coating and ceramic processing 5. Cutting 6. Welding
Non-thermal plasma (non-equilibrium)	$T_{electron} >> T_{ion} \approx T_{gas} = 300$ to 10^3 K nelements $\approx 10^{20}$–10^{21} m^{-3}	1. Air pollution control 2. Polymer coating and treatments 3. Wound healing and cancer treatment 4. Biological cells and tissues 5. Bio-decontamination 6. Cold plasma treatment

Thermal plasma

Development of plasma torches

When the passing flowing gas through an electric arc and producing plasma; this type of device is called plasma torch. The optimal operating power of the plasma torches ranges from few hundred watts to several 100 kW.

Components of plasma torch

The component of the plasma torch is such that the cathode terminal of plasma torch is connected to negative power supply of the torch. It shaped like thin pointed rods but some torches have flat-ended shapes as well. The anode terminal of the torch is shaped like a disc, ring, tube or of nozzle type and can be mounted inside/outside of the torch. Flow pattern of the gas is an important parameter in generating plasma and controls various parameters including jet length of plasma, maximum temperature and cooling of electrodes. Shape of the torch is such that both anode and cathode are fused together in one housing and plasma is limited to flow in one direction. The material used for the construction of plasma torch can be of different materials.

Types and classifications of plasma torch

There are three types of torch: (1) radio frequency torch, (2) alternating current torch, (3) direct current torch. Plasma torches are classified as transferred arc plasma torch and non-transferred arc plasma torch as illustrated in Fig. 1. In transferred arc plasma torch, both cathode and anode are placed in specific distance and anode considered as a work piece. Whereas, in the case of non-transferred arc type torch (plasma), distance between cathode and anode is in few millimeters (Venkatramani 2002; Zhukov 2007). Generally,

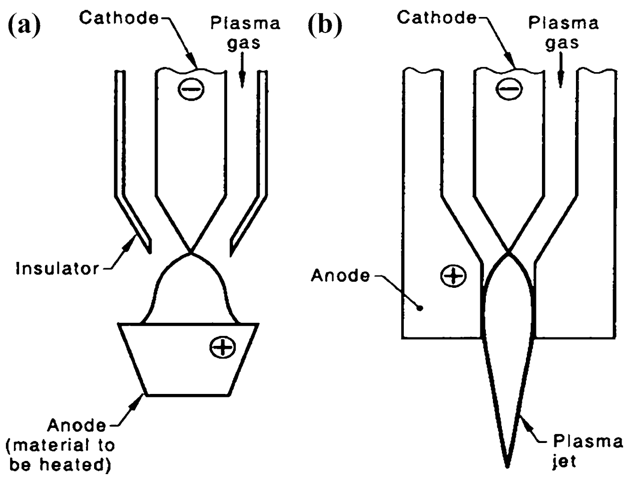


Fig. 1 Schematic diagram of direct current (DC) thermal plasma torches (Murphy 1999): **a** transferred arc, **b** non-transferred arc (copyright permission)

nitrogen, argon, hydrogen and oxygen gases are used in such type of plasma torches.

Solid waste treatment by thermal plasma

The demand of plasma torches is increasing enormously due to its potential benefits which includes, alternatives to fossil fuels, more reliable, cost-effective and to provide small capacity plants. This feature helps in the constructions of mega project more economical. Plasma torches also support zero carbon emission, because gas flow rate in torches are much smaller than conventional heating systems. Many advanced countries are working to build up the setup for plasma research so to potentially reduces the environmental issues (Inaba and Iwao 2000; Chang 2001; Chang and Mahant 1994; Donaldson et al. 1991), for example, municipal wastes (Chang and Mahant 1994; Donaldson et al. 1991), discard tires (Chang et al. 1996), toxic and hazardous materials (Chu et al. 1998), chemicals (Chang and Mahant 1994; Donaldson et al. 1991) or contaminated waste (Tzeng et al. 1998; Yasui et al. 1998) and from steel industries, power plants etc.

Generally, the procedure for waste treatment plants can be describe in three ways (Chang 2001, 2009) as,

1. To gather all solid and liquid discharges even in gaseous forms from water ponds or open air with dilution under specific limit.
2. To help producing building materials, agricultural usage and bio-products from conversion of wastes.
3. Transformation of solid wastes to non-toxic products such as carbon dioxide, nitrogen gas, oxygen to water ponds, landfills and air.

Among several methods, thermal plasma is considered to be the most viable and effective method for solid waste treatment, because in this process, only small amount of toxic products released. Generally, industrial, medical, military and municipality wastes can be treated through the plasma reactors (Inaba and Iwao 2000; Chang 2001; Chang et al. 2005, 1997; Chu et al. 1998; Tzeng et al. 1998; Yasui et al. 1998; Jimbo et al. 1995). However, large volume of industrial and municipal wastes can be treated using incinerator-plasma ash melting system (Chang 2009). In further sections, we will provide the details of thermal plasma applications which dictates the suitability of municipal solid waste treatment, hazardous waste, steel making and plasma jet injection treatment.

Municipal solid waste treatment

The municipal solid waste is an important role in our daily life and it is unavoidable product, the flow diagram of waste management system is depicted in Fig. 2. As we understand, the population of the world increasing day by day and we are facing the problem to store municipal waste. Therefore, we need to have the treatment to store this municipal waste. For this purpose, we used the term named as 'municipal solid waste (MSW) treatment'. The MSW treatment is able to recycle waste material and convert it into useable product (Agamuthu et al. 2009). Now a days, major globally environmental problem is because of MSW, and this is very general in developing countries. Due to the heterogeneous nature, it emerges as challenging problem. MSW is directly linked to our community, because it may include hazardous and non-hazardous waste material. This problem is also challengeable for rural and developing countries due to low socio-economic level of population and lack of awareness. Domestic solid waste, commercial solid waste and industrial solid waste are the main sources which are generated by municipal solid waste (Chandler 1997). Number of studies have been performed on this issue of MSW treatment, some of them are listed as follows:

- Nam and Capereda (2015) introduced RSM (response surface methodology) technique to understand effects of process conditions and compositions of biomass changing.
- Nam et al. (2017) described the advantage of dairy manure mixed with sand and bedding for gasification.
- Nam et al. (2015) investigated three bench-scale auger, batch and fluidized bed reactors through rice straw in specific temperature.
- Arazo et al. (2017) investigated fluidized bed reactor and used optimization technique for bio-oil through fast pyrolysis.

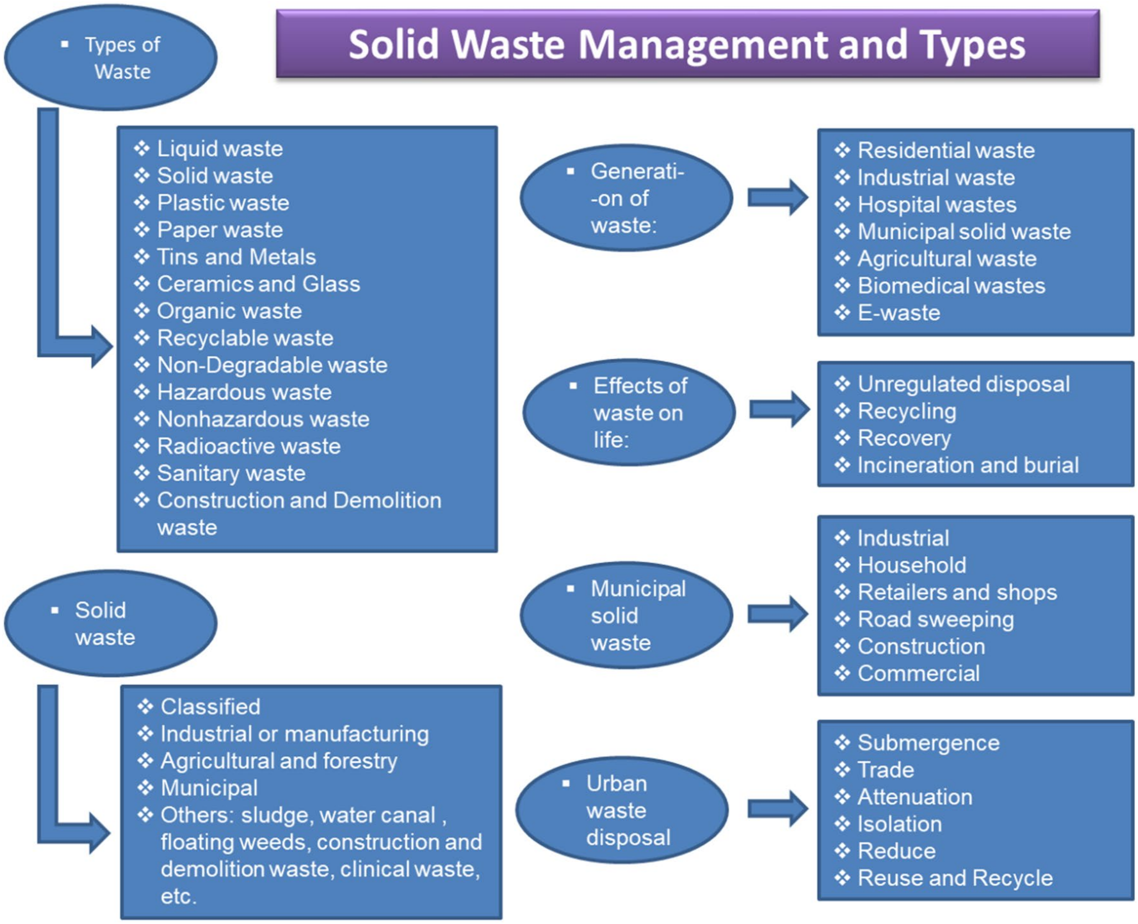


Fig. 2 Solid waste management and their types

- Meng et al. (2015) introduced two methods and provide comparison of physicochemical and compositional properties of aged bio-oils.
- Wang et al. (2016) doing research on municipal wastewater especially targeted to hydrothermal liquefaction of microalgae and metal testing with specific pressure and temperature.
- Omoriyekomwan et al. (2016) investigated catalytic fixed-bed and microwave pyrolysis of palm kernel shell through carbon, lignite char and microwave receptors.
- Yuan et al. (2015) introduced the major methods for processing municipal solid waste (MSW) harmlessly and they reputed the effectiveness of torrefaction for removing moisture and improving material properties.
- Kambo and Dutta (2015) provide the comparative review for biochar and hydrochar, this review explain the detail analysis of production, physic-chemical properties and applications.
- Mashayekh-Salehi and Moussavi (2015) investigated pharmaceutical compounds in aqueous solution through material research.

Thermal plasma plant assisted by ash melting volume reduction method was developed and commercialized at Matsuyama city in Japan with a capability to treat 52 tons of ashes/day (Chang 2009). In the schematic of plasma ash melting system as illustrated in Fig. 3, it can be observed that two DC 1.5 MW plasma torches are used as heat source with upper and lower columns. The torches are operated from 0.4 to 1.3 MW which is generated by waste incinerations depending upon the ash volume required to treat. In this case, no electricity is required from external source. A typical plasma melting temperature ranges from 1100 to 1700 °C depending upon the plasma operating power source (Chang 2009).

Hazardous waste: health care treatment

The wastes from healthcare centers are usually classified into general waste and hazardous wastes. Hazardous needs to be handle in special way but general waste does not need to handle with intense care. Medical usage includes anatomical wastes (tissues and organs), blood and fluids, discarded

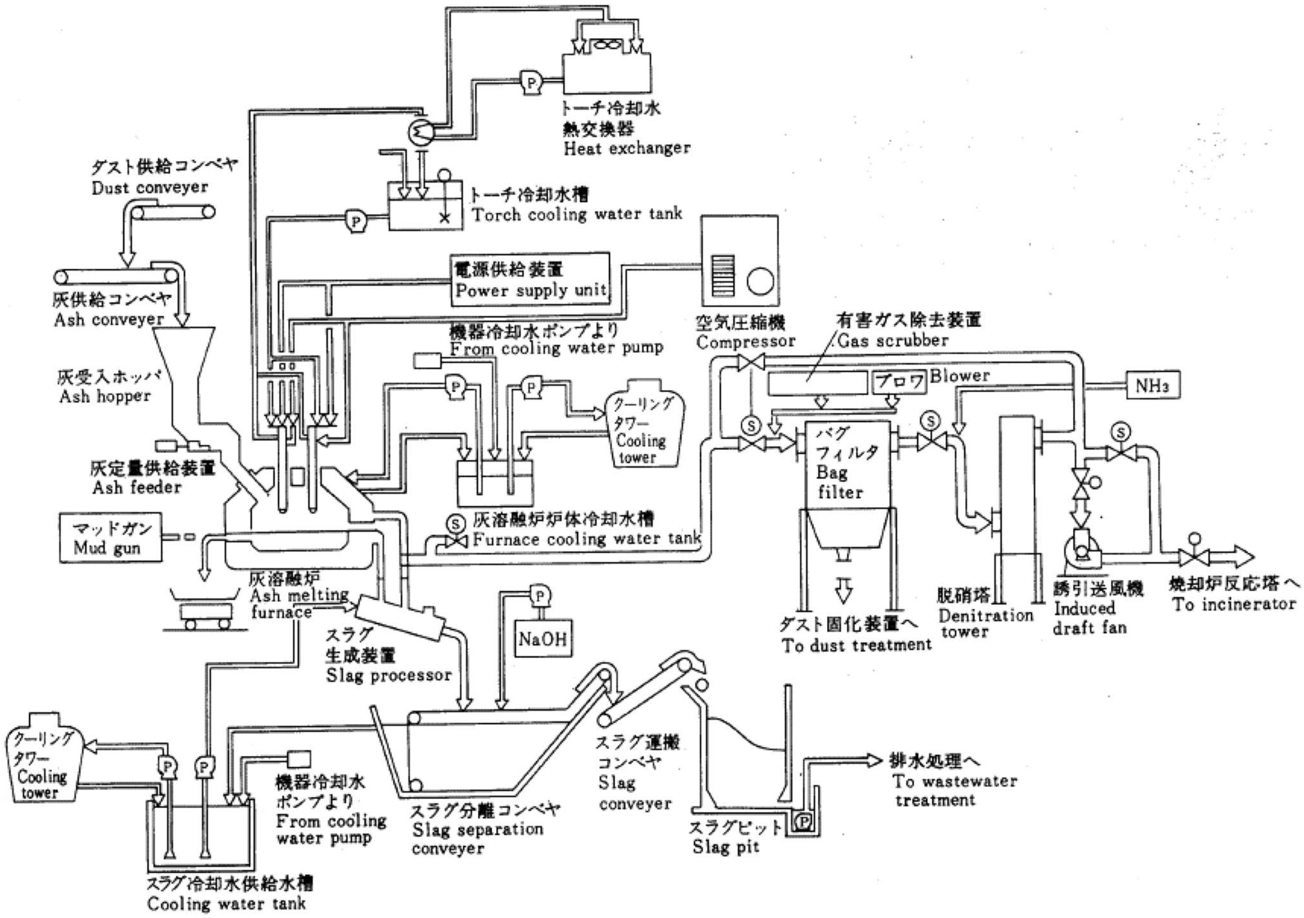


Fig. 3 Plasma ash melting system in Matsuyama (Chang 2009) (with copy right permission)

medicines, pathological and highly infectious wastes. For the medical purposes, the thermal plasma contains ultra-violet radiations and high temperatures, which can kill bacteria and micro-organisms. In addition, drug structure and active ingredients which constitutes only a small fraction of actual mass e.g., cytotastic and cytotoxic drugs can be destroy with thermal plasma (Nema and Ganeshprasad 2002). In hospital incinerates, usually plasma furnace used to treat bottom ash through coal fired power plant (see Table 3). Number of studies are reported in well-known scientific platforms such as Gensburg et al. (2009) addressed the major incident of love canal residents, Li et al. (2015) described the life cycle assessment and hazardous waste in Eastern China, Saleh (2012) demonstrated the phytoremediation efficiency of live floating plant, Eskander and Saleh (2012) provide the detail analysis of cement mortar-degraded spinney waste and radioactive waste, Eskander et al. (2013) investigated liquid scintillator waste, leachant type and leaching temperature.

For the hazardous waste, the republic of Korea tested the performance of plasma torch system for the treatment of medical wastes. They used two types of torches in treatment denoted by N1 and N2 (see Table 4) (Park et al. 2005). The temperature exceeds to 1500 °C when N2 is in operation and slag is flowed out and gathered into the collector region. The

Table 3 Hospital incineration and chemical analysis (Cedzynska et al. 1999) (with copyright permission)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	Mn_3O_4	TiO_2	CaO	Na_2O	MgO	K_2O	P_2O_5	SO_3
Hospital incinerator bottom ash	47.35	3.05	7.35	a	a	16.25	a	2.45	a	0.30	0.48
Coal power plant fly ash	50.02	23.20	9.25	0.15	0.96	4.08	0.96	2.48	3.40	0.32	0.52

Table 4 Plasma torch system built in Korea for the treatment of medical wastes (Park et al. 2005) (with copy right permission)

Parameters	N1 plasma torch	N2 plasma torch
Power	40–45 kW	65–85 kW
Airflow	4–6 g/s	7–9 g/s
Plasma jet temperatures	3.0–4.0 K	2.5–4.0 K

composition of slag dictates that it is chemically resistive and vitreous and not contains any organic components with a density of 2.6–2.8 K kg/m^3 (Park et al. 2005).

Steelmaking

Comparatively large amount of wastes in the form of dust as well as metals such as iron, lead, zinc, chromium, nickel, molybdenum is recovered from steel manufacturing industries. Table 5 presents annual global solid waste from steel industry. These metal wastes are sometime extremely hard but are economical and is possible to extract and recycle them. Furthermore, these wastes are hazardous due to the leachability of hazardous components.

Treatment through plasma jet injection

Organic contaminant present in aqueous solution creates many problems in some industries such as paper, pulp and aluminum. Therefore, development of treatment method for liquid solution is very important. Considerable numbers of efforts and techniques are made to find an effective solution for treatment of these contaminants in liquids. Among them, includes various types of plasma and incineration. In Fig. 4, the plasma treatment of aqueous solutions by experimental reactor is shown. The treatment contains plasma which transfer high electrical energy into liquid phase and generates highly active compounds such as ozone, hydroxyl radicals, hydrogen peroxide, etc. (Munholand et al. 2006; Armstrong and Soucy 2007; Boudesocque et al. 2007; Safa and Soucy 2014; Samokhin et al. 2010; Fortin et al. 2000; Yargeau et al. 2004; Soucy et al. 2006). Hafnium doped

Table 5 Annually worldwide solid waste from steel industry (Ye et al. 2003) (with copy right permission)

Major concerns	Free lime, heavy metals	Leaching of heavy metals	Too low Zn for recovery	Too high Zn for recycling	Hazardous wastes
World (Mtons)	BOF slag 90	EAF slag 25	BOF dust 15	– –	EAF dust 4

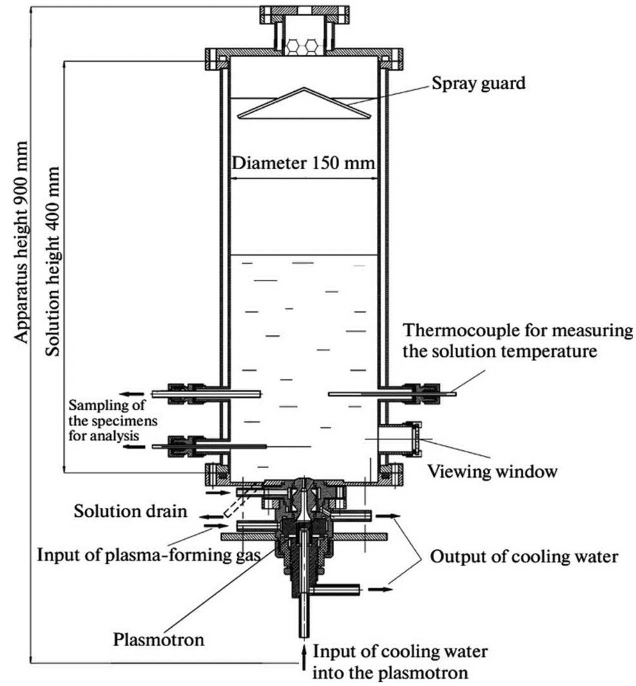


Fig. 4 Plasma treatment of aqueous solutions by experimental reactor (Samokhin et al. 2010) (with copyright permission)

copper rod material is also being used for solving the cathode erosion problem in oxidative medium (Yuan et al. 2010).

Non-thermal plasma

Treatment through dielectric barrier discharge (DBD) plasma

Generally, all plasmas defined into two major categories in terms of electric density or temperature, which we called thermal or non-thermal plasmas. Thermal plasma (arc discharges, torches or radio frequency) is nearly fully ionized while non-thermal plasma (biomedical applications: plasma jets, coronal discharge plasma sources, DBD plasma sources) is only partially ionized. In thermal plasma (hot plasma: $T_e \sim T_{gas}$, plasma torches or high pressure discharges), which approaches a state of local thermodynamics equilibrium, while motion of ions can be ignored in non-thermal plasma (cold plasma: $T_e >> T_{gas}$, low-pressure discharges or dielectric barrier discharges). Etching, chemical vapor deposition, plasma polymerization, surface structuring are example of plasma technology, which are interrelated with electronics, semiconductor industry and materials science (Domonkos et al. 2018, 2016, 2020; Ticha et al. 2020; Steinerova et al. 2021). This technology has a long history but currently cold atmospheric pressure plasma (CAPP) has an active role especially for industrial sectors. Usually, CAPP is suitable for surface treatment such as metal, glass, polymer, etc. (Cvelbar et al. 2018; Talviste et al. 2019; Medvecka et al. 2020; Thomas et al. 2019). Treatment through cold plasma are already used in medical issues and laboratory equipment such as bacteria, fungi, viruses, biofilms, surgical instruments, pharmaceutical devices, implants, dialysis tubes, glassware, plastic tubes, pipette tips, beds, floors, etc. (see Fig. 5). Direct and contact through source of micro-organisms are the two ways for contamination and the process in illustrated in Fig. 6. For example, a patient

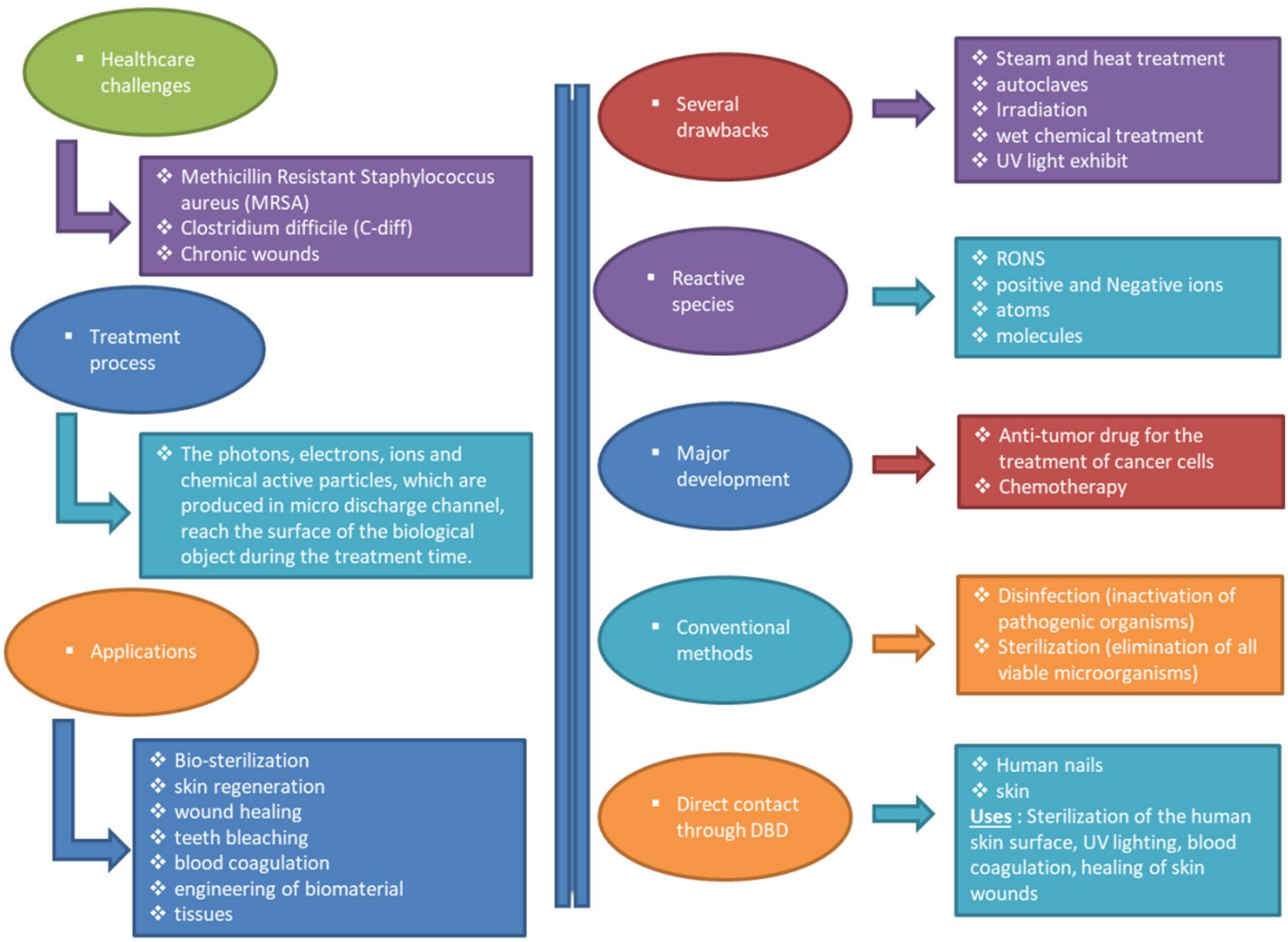
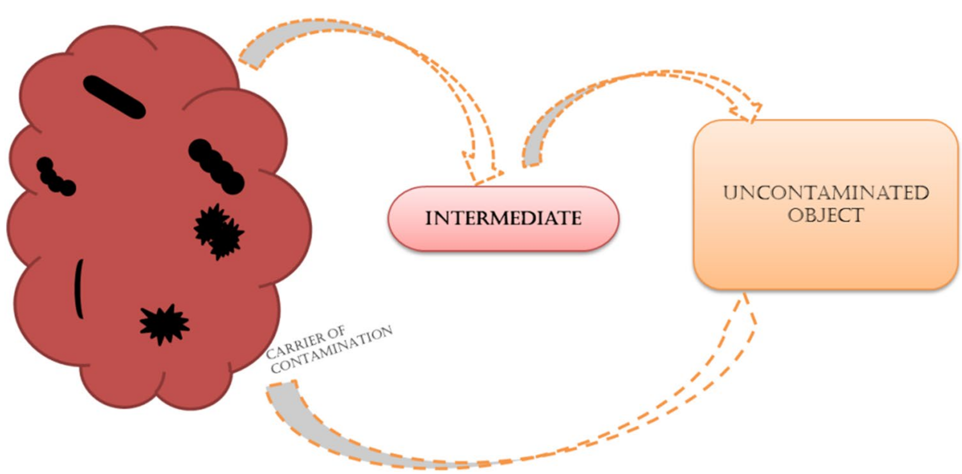


Fig. 5 Flowchart shown the schemes and characterization of dielectric barrier pulsed discharge plasma for bio-medical applications

Fig. 6 Contamination process (Laroussi et al. 2012)



sneezes into his hand and then shakes hand with other people or touch the door handle or eat something else. This is a way to transfer viral particles to other by formation of biofilm (Fig. 7). Some past research are depicted as follows:

- Laroussi (2009) tried to solve some fundamental questions which are directly related to cold plasma treatment and for medicines.
- Laroussi (1996) developed a new approach based on various plasma technologies.
- Kelly-Wintenberg et al. (1998) and research team studied the method of one atmosphere uniform glow discharge plasma and make it possible to provide for antimicrobial active species to surfaces.
- Herrmann et al. (1999) and team members studied atmospheric pressure plasma jet and high velocity effluent stream of highly reactive chemical species.
- Laroussi et al. (2000) found the effective agents for biological decontamination/sterilization through non-thermal gaseous discharge.
- Laroussi (2002) prepared the review for non-thermal plasma decontamination and addressed some inline topics such as biological and germicidal effects of atmospheric pressure.
- Laroussi (1999) published the US Patent in the field of plasma glow discharge.
- Shekhter et al. (1998) provide the detail of plasma chemical method and its utilization for health issues.
- Stoffels et al. (2002) and research team are working on non-plasma source. They address the utilization of this source especially for biomaterials treatment.
- Woloszko et al. (2002) and research team are working on saline solutions and they reported sodium chloride and barium chloride saline solutions.

Plasmonic material

In this review report, we reported a newly introduced method of plasmonic nano-material, an interesting material for diverse applications including energy sectors, solar/fuel cells and sensor, solid waste, bio-medical issues and laboratory equipment. The results of this method are illustrated in Fig. 8 which successfully demonstrated the chemical detection (Khan et al. 2020). Previously, in the literature, this method was used in vacuum, while in the reported data, a quite new approach of flowing gas is being adopted to test it at atmospheric pressure. This approach seems to facilitate nanofabrication on industrial scale.

Conventional method is used since several decades and it is consider a versatile technique but it does not incorporate for industrial application. Therefore, traditional method is suitable for industrial application such as vacuum requirements, limited area deposition, coating of irregular objects and long deposition time (Khan et al. 2020; Eason 2007; Mirza et al. 2014; Donnelly et al. 2006; Mihailescu and Caricato 2018).

Some of the applications of atmospheric pressure dielectric barrier discharge (DBD) plasma is as follows:

- Plasmonic active nanoparticle (NP)-coated surfaces for surface enhanced Raman spectroscopy (SERS) application for chemical detection.
- Enhanced detection in LIBS.
- Surface modification.
- Mechanisms can be extended to fast switching.
- Nanomaterial fabrication using DBD plasma stream.
- Antibacterial silver coating of surgical devices.
- Surface etching/modification.

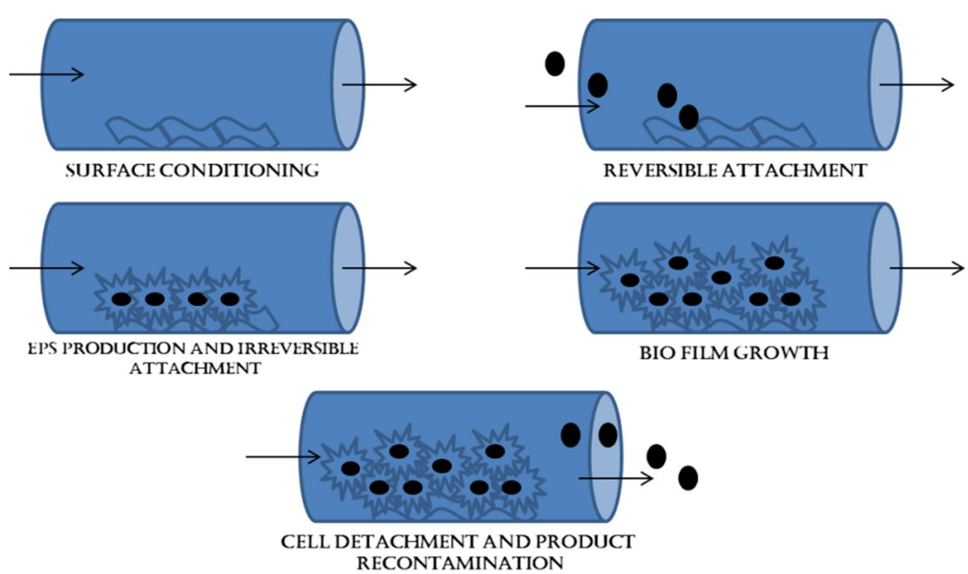


Fig. 7 Formation of biofilm and stages (Laroussi et al. 2012)

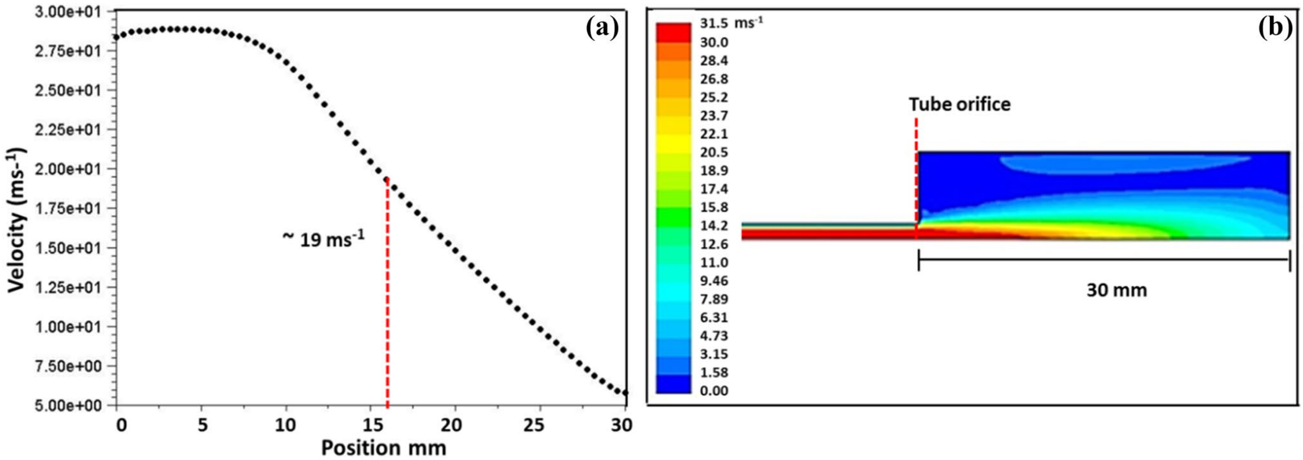


Fig. 8 **a** Velocity magnitude contour, **b** velocity profile of argon flow at 7 L/min (Donnelly et al. 2006)

This is new development and is a great contribution in the field of nanotechnology; facilitates the fabrication of nano-material for energy applications, solid waste treatment through non-thermal plasma, energy devices and open new rooms for further research.

Conclusion

In this review, research is successfully define thermal plasma treatment and non-thermal plasma with its utilities in nano-scale high-tech plasmonic materials. We have elaborated globally analysis of solid waste treatment through thermal plasma and dielectric barrier discharge (DBD) plasma research. For this purpose, we have defined the conceptual detail of arc plasma torches (transferred and non-transferred torches) and provided the short review of our in-depth conducted research for solid waste treatment through thermal plasma such as solid waste, healthcare, steelmaking, and treatment through plasma jet injection. Furthermore, a short review for the treatment through dielectric barrier discharge (DBD) plasma, and plasmonic material are included. In the focus of deep analysis, treating solid waste issues through thermal plasma is the best choice and the application of non-thermal plasma such as DBD is the most useful and latest approach for plasmonic material.

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Declarations

Conflict of interest All authors declare no conflict of interest.

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