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A Sustainable Integration Approach of Chlor-Alkali Industries for the Production of PVC and Clean Fuel Hydrogen: Prospects and Bangladesh Perspectives

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Highlights:

- Expansion of chlor-alkali industries in Bangladesh has been stopped because of a lack of Cl_2 demand.
- Yearly PVC piping and fitting material demand is increasing in Bangladesh at a rate of about 20%.
- Integration of chlor-alkali and PVC industries is a feasible solution for the sustainable development of caustic industry.
- The hypothesized PVC plant can consume byproduct Cl_2 of 78,000 MT/y from chlor-alkali plants.
- The byproduct H_2 can be utilized to produce H_2O_2, power, and operating fuel cell-based vehicles.

Abstract: The chlor-alkali industries produce caustic soda (NaOH), chlorine (Cl_2), and hydrogen (H_2) as primary products. In 2021, the global chlor-alkali market was valued at $63.2 billion. The article evaluates the global aspects of chlor-alkali industries and prospects for Bangladesh. The current production capacity of NaOH from the chlor-alkali industries in Bangladesh is around 282,150 metric tons/year (MT/y). The by-products, chlorine (Cl_2) of 250,470 MT/y and hydrogen (H_2) of 7055 MT/y, are produced domestically. The local demand of Cl_2 is 68,779 MT/y. However, there are no systematic utilizations of the residual Cl_2 and vented H_2, which threatens the sustainability of the chlor-alkali industries. The article prefigures that a 150,000 MT/y PVC plant can utilize 45.2 % of residual Cl_2 of chlor-alkali plants, which would be an economical and environmental milestone for Bangladesh. The residual Cl_2 can earn revenue of 908 million USD/y, which can be utilized to import ethylene. For the sustainable utilization of vented H_2, production of H_2O_2, fuel cell electric vehicle (FCEV) and H_2 fuel-cell-based power plant are the feasible solutions. Thus, for the long-term growth of the chlor-alkali industry in Bangladesh and other developing countries, systematic utilization of Cl_2 and H_2 is the only feasible solution.

Keywords: chlor-alkali plant integration; chlorine and H_2 utilization; PVC market; clean fuel; environmental sustainability

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1. Introduction

Caustic soda (NaOH) is used as a raw material and as an associated chemical in several industries, e.g., chemical, automotive, water treatment, food, and paper, due to its highly versatile characteristics. It is extensively used in the production of soap, glass, drugs, paper and pulp, textile, leather, and sugar, and in water treatment plants and effluent treatment plant-based industries. The demand for caustic soda is increasing globally (demand in 2019 was 81.9 million metric tons (MMT)) due to the growth of these industries [1]. The market for caustic soda is expected to rise to US$ 106 billion in 2023 [2] with a compounded annual growth rate (CAGR) of 4.5% in the forecasted period of 2022–2027. The Asia

Pacific region dominates caustic soda production and consumption [3]. Asia-Pacific has a strong position in the chlor-alkali market because of a number of factors, such as increased production capacity, lower energy costs, strong regional demand, lower prices than in other regions, and a strong supply chain [4]. China, India, South-East Asia, and South America are expected to have the most growth in the caustic soda market due to increased industrialization, urbanization, and population.

The chlor-alkali process has evolved in three stages, e.g., (i) diaphragm process (1st generation), (ii) mercury process (2nd generation), and (iii) membrane cell process (3rd generation) [5]. The modern chlor-alkali plants are mostly based on the membrane cell technique. The systematic evolution of these technologies was based on economic, energy, and environmental sustainability. The two main by-products of the membrane cell-based chlor-alkali process are chlorine (Cl_2) and hydrogen (H_2).

Cl_2 is an important raw material for different types of industries. The end-use sectors for Cl_2 include chemicals, textile, water treatment, pharmaceuticals, paints, plastics, and PVC industries (Figure 1) [6] and the world production crossed 75 MMT in 2019. In 2020, the global market capture of Cl_2 was US$ 33.5 billion, with a CAGR of 4.5% in the forecasted period of 2022–2027 [7]. Canada, the USA, Japan, and France dominate the global supply chain of Cl_2.

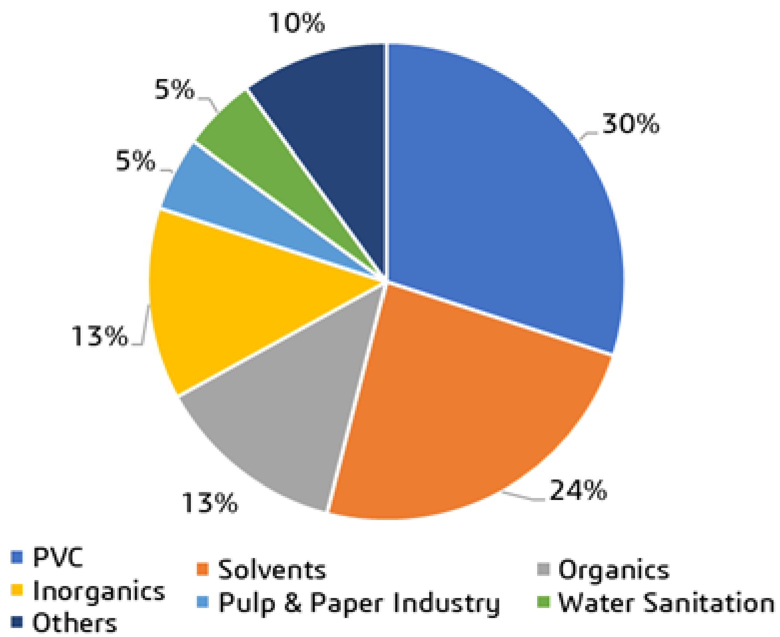

Figure 1. The uses of Cl_2 in various sectors [8].

The chlor-alkali industries convert its gaseous Cl_2 into hydrochloric acid (HCl), sodium/calcium hypochlorite ($NaOCl/Ca(OCl)_2$), polyvinyl chloride (PVC), ammonium/zinc/calcium chloride (NH_4Cl, $ZnCl_2/CaCl_2$), chlorinated paraffin wax (CPW), and stable bleaching powder (SBP).

The utilization of Cl_2 for PVC production is a vital usage of chlor-alkali industry-generated Cl_2 in the current world [9]. Cl_2 demand is accelerated by the growing need for PVC in construction, automotive, and composite manufacturing applications. In addition, the rising demand of the packaging industry is driving the PVC market even higher. The current PVC technology uses the Cl_2 produced by electrolysis. In the electrolysis process, the electricity is applied to seawater or industrial-grade salt solution (brine). This technology is very energy-intensive, thus the cost of PVC increases with increasing electricity prices [10].

East Asia and the United States were the leading PVC suppliers over the last decade. In recent years, China has become the largest consumer and producer of PVC. China has transitioned from a net importer to a net exporter of PVC, surpassing the United

States in both capacity and volume of PVC manufacturing [11]. In terms of revenues, ChemChina is the largest PVC manufacturing company in the world with a revenue of USD 46.5 billions/y. Whereas the two largest producers in terms of annual production capacity are Zhongtai Chemical Co., Ltd., Urumqi, China (with a production capacity of 2.2 million tons/y) and Xinjiang Tianye Co., Ltd., Shihezi, China (with a production capacity of 1.2 million tons/y) [11]. In China, either calcium carbide or ethylene-based PVC production is followed. However, 80% of PVC production in China is based on calcium carbide. The PVC resin manufactured with the calcium carbide technique is utilized in the construction of low-end pipes [12]. While PVC resin produced by the ethylene-based technique has minimal vinyl chloride residue and is utilized to produce refined high-end PVC items, which is not possible with the calcium carbide method. In the USA, Dupont (Dow Chemical, Midland, MI, USA) is the leading PVC manufacturer, followed by Westlake Chemical Corporation, Houston, TX, USA and Axiall, Atlanta, GA, USA. Other than the Chinese and American PVC manufacturers, Taiwan-based Formosa Plastics Corporation, Kaohsiung, Taiwan, South Korea-based LG Chem Ltd., Seoul, Korea, Japan-based Shin-Etsu Chemical Co., Ltd., Tokyo, Japan and Mexico-based Orbia, Mexico City, Mexico are the leading suppliers of PVC in the world market (Figure 2) [13].

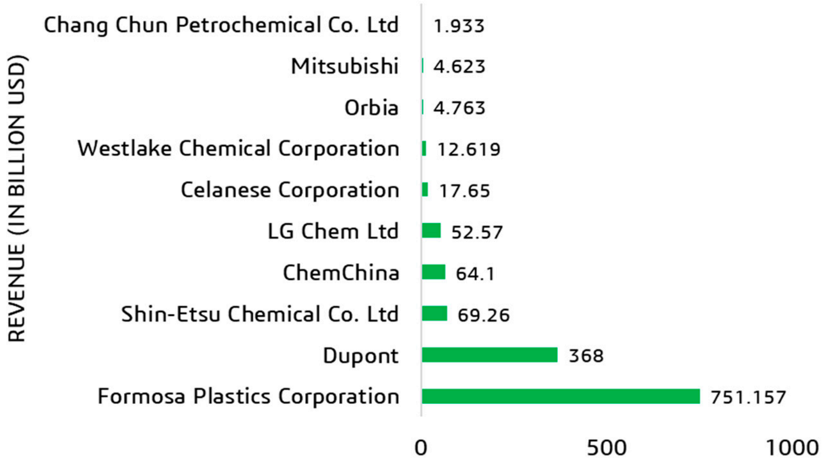

Figure 2. World's Leading PVC Manufacturers in Terms of Market Capitalization (in billion USD for the year 2022) [13].

Another prospect of chlor-alkali industries is the utilization of waste H_2. Most of these industries vent the produced H_2, which is a challenging concern for the sustainability of the chlor-alkali plant. H_2 is a fundamental building block for the production of industrial feedstock. In recent years, the use of H_2 for power generation and transportation has unveiled its potential for a greater purpose [14]. The chlor-alkali industry-generated H_2 can be an important asset for creating a sustainable economy for the sustainability of the integration process.

In this work, we have studied different chlor-alkali processes and figured out the opportunities of the industry on a global scale. We carried out an extensive case study in Bangladesh to further emphasize the opportunities the chlor-alkali industries can provide worldwide. In Bangladesh, the basic chemical industries include chlor-alkali plants, chlorinated products, sulfuric acid plants, and hydrogen peroxide plants [15]. The current domestic demand for chlor-alkali-generated caustic soda is around 400,000 MT. In Bangladesh, only five companies produce chlor-alkali by membrane cell technology and those are Tasmin Chemical Complex Ltd. (Tasnim), Dhaka, Bangladesh, Samuda Chemical Complex Ltd. (Samuda), Dhaka, Bangladesh, Global Heavy Chemicals Ltd. (GHCL), Dhaka, Bangladesh, ASM Chemical Industries Ltd. (ASM), Dhaka, Bangladesh, and SR Chemical Industries Ltd. (SR), Rajapur, Bangladesh (Table 1). The chlor-alkali industries of Bangladesh convert the Cl_2 into HCl, NaOCl, NH_4Cl, CPW, and SBP. However, the converted chlorinated products have less demand than the production, therefore, discharged into the water bodies which is alarming for the environment and mankind. The byproduct Cl_2 of the chlor-alkali industries in Bangladesh is underutilized; for the sustainable development of the chlor-alkali plant in Bangladesh or anywhere in the world, the proper utilization of Cl_2 is an important criterion. Among many, there is an opportunity to utilize Cl_2 from these plants to produce PVC. Globally, 40% of Cl_2 from chlor-alkali process is utilized in PVC production, whereas in India, it is only 6.64% and in Bangladesh, it is 0%.

In recent years, the demand for PVC in Bangladesh has increased tremendously and the current plastic demand increasing rate is 8%. The total sale of plastic items in Bangladesh is about 3300 million USD/y of which 25% are PVC products. All the PVC products are produced based on imported and recycled PVC resins. The imported plastic resin market reached a value of more than 330 million USD/y (local source). Since PVC consumption has increased; by-product Cl_2 of chlor-alkali plants can be used as raw materials for PVC resin production to achieve a sustainable integration of chlor-alkali and plastic industries in Bangladesh. The development of PVC resin production industries in Bangladesh can create a scope of consumption of Cl_2. Recently, Meghna Group of Industries (MGI) is erecting a PVC resin production plant named 'Meghna PVC' in Narayanganj, Bangladesh and the plant is going for commissioning in September 2022 [16]. The production capacity of the plant is only 150,000 MT of PVC resin.

The sustainable growth of the energy sector depends on the search for renewable sources [17]. H_2 has an excellent potential to be used as an industrial feedstock in the ammonia, steel, and hydrogenation process. The H_2 obtained from chlor-alkali can be routed to the hydrogenation unit of the H_2O_2 production plant and used in H_2 fuel cell technology for FCEVs and power plants to solve the energy crisis in Bangladesh [18].

Some of the Sustainable Development Goals (SDGs) completely align with the concept of the chlor-alkali integration approach. The sustainable chemical consumption by the proper utilization of Cl_2 and cleaner energy production through H_2 power plants are the noteworthy direction of the integration initiative.

Therefore, in the current study, we took an approach to find the sustainable application of chlor-alkali-derived by-products. We have studied the different chlor-alkali process and their evolution. The opportunities of the by-products were systematically discussed. To obtain an in-depth analysis we have studied the integration approach of the chlor-alkali and PVC process to ensure the proper use of gaseous Cl_2 and clean fuel H_2. As a case study, we have chosen Bangladesh as the data from several industries were available to the authors. The specific objectives of the study are (i) analyzing the opportunities of chlor-alkali process, (ii) surveying the production process of five major chlor-alkali industries in Bangladesh, (iii) market scenario analysis of PVC products and PVC resin consumption in Bangladesh, (iv) feasibility study of PVC resin production from chlor-alkali industry-derived gaseous Cl_2 to set up an integration approach in Bangladesh, (v) reducing the effect of forecasting the harmful effects of Cl_2, and (vi) recommendations of Cl_2 transportation.

This work would provide a proper framework to evaluate the opportunities for integration of chlor-alkali and PVC industries in any country including Bangladesh. Moreover, the sustainable integration of chlor-alkali plants for efficient utilization of Cl_2 and H_2 would be in line with the SDGs. Analysis of the current Cl_2 management strategy in different chlor-alkali plants in Bangladesh will ensure the proper uses of Cl_2. Moreover, the feasibility of PVC Resin production from Cl_2 is explored.

2. Outline of Methodology

The chronological outline of the paper is (i) studying the chlor-alkali and PVC process, (ii) studying the opportunities of the chlor-alkali derived by-products, (iii) the collection of Cl_2 disposal and consumption data from the chlor-Alkali plants, (iv) economic feasibility of PVC industries utilizing Cl_2 produced in chlor-alkali plants, (vi) probable H_2 utilization plan in H_2O_2, steam, and power generation.

To give the readers a better understanding on the integration approach, we have initially discussed the different chlor-alkali processes and their chronological development. The potential of by-products was then portrayed systematically on the global and Bangladesh scale. As there are no established integrated plants in Bangladesh, we have performed an extensive case study to understand the initial feasibility of the chlor-alkali and PVC process integration.

We have selected five chlor-alkali industries (GHCL, ASM, Samuda, Tasmin, and SR) of Bangladesh as a basis. We have studied their production line and overall manufacturing process. We have gathered information regarding the amount of chlorine discharged from these industries and market analysis of the uses of chlorine-related products.

In addition, we have analyzed the current PVC market scenario in Bangladesh. We have selected the Meghna PVC plant (a private company) as a potential customer for the production of Cl_2-based PVC. To be more profitable, the PVC plant ideally should be close to the chlor-alkali plant. However, as this is not the case for Meghna PVC, we have looked at Cl_2 transportation options and made acceptable recommendations to improve the situation. There are no such established formula to predict the actual profitability of the process. Hence, we have studied a case based on China for the sustainability prediction of the integration of chloro-alkali industries.

Currently, the government of Bangladesh has no plan to utilize the vented H_2, therefore we have figured out the probable H_2 utilization routes. The USD used in this paper indicates the April 2022 USD values.

3. Chlor-Alkali Process

The chlor-alkali process is an industrial process for the production of caustic soda (NaOH) and chlorine (Cl_2) by the electrolysis of brine solutions [19]. From the days of the diaphragm process (Griesheim cell, 1885) and mercury process (Castner-Kellner cell, 1892) to the contemporary membrane cell process (1970), the chlor-alkali process has come a long way, with a significant reduction in power consumption and CO_2 emissions [5]. These processes differ in terms of electrode (anode and cathode) reactions and the techniques of product separation [20]. In most of the modern chlor-alkali processes (62%), the membrane cell technique has been utilized (Figure 3).

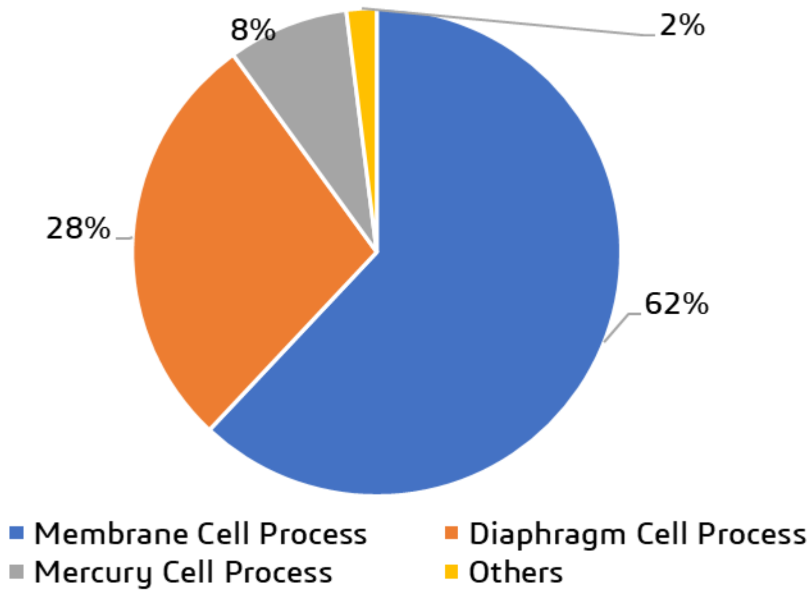

Figure 3. The division of capacity among the three principal cell technologies used in the world for chlor-alkali process [5].

The anode and cathode materials are different in these processes. In the Griesheim cell of the diaphragm process, asbestos, polymer-modified asbestos, or non-asbestos separators are used. Ion-exchange membranes are employed in the membrane cell technique. Cell voltages differ from 2.90–3.60 V for diaphragm cells, 3.15–4.80 V for mercury cells, and 2.35–4.00 V for membrane cell process [21].

The low energy consumption, no requirement of mercury or asbestos, low operating and investment cost, and high purity caustic of membrane cell process make it more viable than the other two processes. However, in the membrane cell process, high purity brine is required. The comparative analysis of these three techniques has been presented in Table 1.

Table 1. Comparative analysis of Diaphragm, Mercury and Membrane cell process [22].

Parameters	Diaphragm	Mercury	Membrane
Anode	RuO_2 + TiO_2 + SnO_2 coating on Ti substrate	RuO_2 + TiO_2 coating on Ti substrate	RuO_2 + IrO_2 + TiO_2 coating on Ti substrate
Cathode	Steel (or steel coated with activated nickel)	Mercury	Nickel coated with high area nickel-based or noble metal-based coatings
Separator	Asbestos, polymer-modified asbestos, or non-asbestos diaphragm	None	Ion-exchange membrane
Brine quality requirement	Low quality	Low quality	Very high quality
Cell voltage	2.90–3.60 V	3.15–4.80 V	2.35–4.00 V
Current density	0.8–2.7 kA/m^2	2.2–14.5 kA/m^2	1.0–6.5 kA/m^2
Power required/MT Cl_2 produce	3200–3800 kWh	3100–3400 kWh	2400–2900 kWh
Product NaOH concentration	12–15%	50%	30–32%
Product quality (50% NaOH)	Low quality	High quality Mercury levels: <1 ppm	High quality
NaCl content $NaClO_3$ content	High salt content~1.3% $NaClO_3$ content: 0.3%	<30 ppm <1 ppm	<50 ppm –
Chlorine quality (Oxygen content)	between 1.5–2.5%	<0.1%	between 0.5% and 2%
Air emission	Release asbestos	Release mercury vapor	–

In the 1970s, membranes were employed in the chlor-alkali industries, when the invention of ion-exchange membranes established a new method of chlorine production, which is called the membrane electrolysis process. DuPont (Nafion) created the first ion-exchange membranes at the start of the 1970s, followed by Asahi Glass (Flemion), which established the first industrial membrane facility in Japan in 1975 in response to Japanese environmental restrictions on the conventional chloro-alkali process. Since 1987, essentially all-new chlor-alkali plants in the world have adopted the membrane process [5]. The membrane cell process reduces the release of highly toxic mercury to the surroundings but increases the release of moderately toxic substances, e.g., chloride and chlorate as the membrane cell is less tolerant of contaminants and demands higher purity brine [19]. Isabel Garcia-Herrero et al. reported the life cycle analysis (LCA) of the three techniques of chlor-alkali process. The results suggest that the mercury process is the least environmentally sustainable, owing mainly to the mercury-related environmental burdens and, to a lesser extent, to its electric energy consumption, whereas membrane cell technology is the most environmentally sustainable and low energy consuming process [23]. In our study, we have restricted our discussion on the membrane cell process, as Bangladeshi chlor-alkali industries are using this process.

The modern membrane technologies use a cation exchange membrane between half-cells to produce Cl_2 and NaOH from the electrolysis of brine solutions, which enables the safe manufacturing of Cl_2 and NaOH [24]. Due to the rigorous standards for brine purity imposed by membrane cells and during the product's recovery stage, the chlor-alkali industry presents a potential field of application for other membrane technologies in addition to the ion-exchange membranes [5].

The chlor-alkali process can be broken down into three primary stages: (i) the first stage involves the preparation and treatment of brine; (ii) the second stage involves electrolysis; and (iii) the final stage involves product recovery [25] (Figure 4).

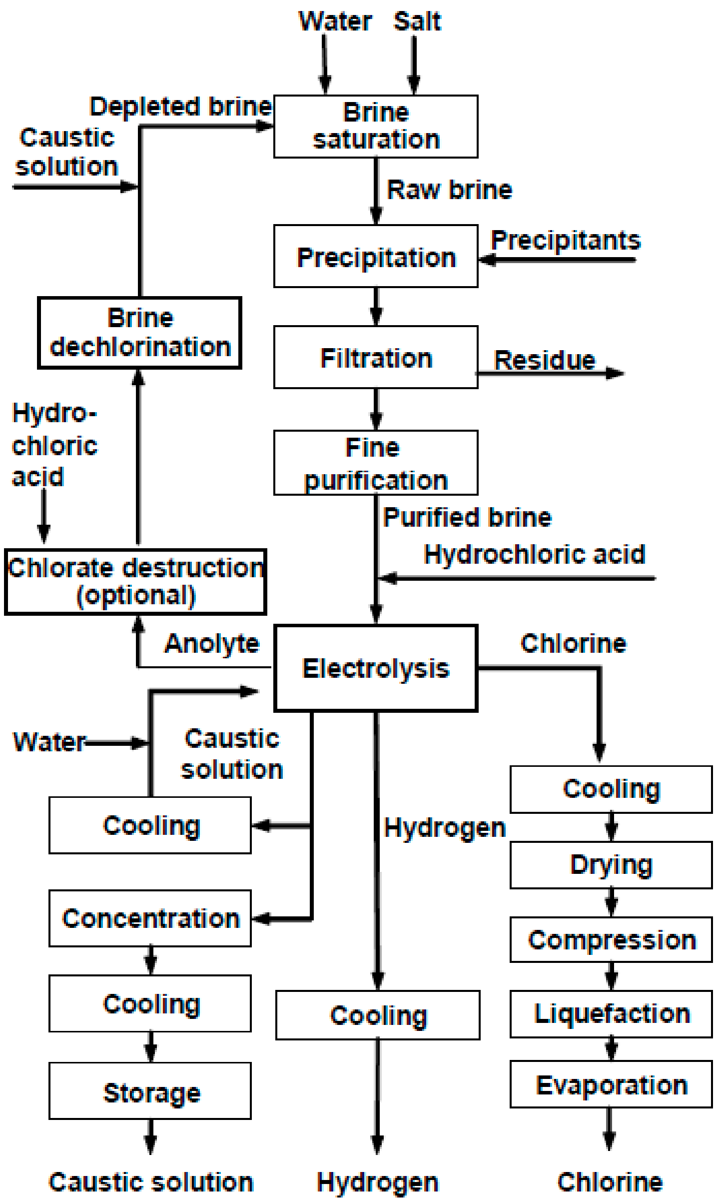

Figure 4. Process flow of simplified membrane cell process [26].

Before being employed in a cell operation, brine must first be purified according to membrane cell technology standards. Precipitation with OH^- and CO^{3-} removes the hardness and heavy metals. Acidification is the last step in the brine preparation process where microfiltration and nanofiltration, two types of membrane technology, are both employed [24]. For microfiltration and nanofiltration polytetrafluoroethylene (PTFE) membranes and polymer nanofiltration membranes are used, respectively [27]. In the electrolysis process, a chloride salt solution (e.g., NaCl) is decomposed electrolytically by passing a direct current through it. There are three basic processes for the electrolytic production of chlorine: the diaphragm cell process, the mercury cell process, and the membrane cell process (ion-exchange membranes).

For ion-exchange membrane selection, several characteristics are considered, e.g., strong perm-selectivity for counterions (exclusion of co-ions), high ionic conductivity, and superior mechanical, form, and chemical stability [25]. The cathode side is separated from the anode side by the ion-exchange membrane. The separator is a bilayer membrane composed of perfluorocarboxylic and perfluororosulfonic acid-based films. The former is responsible for the membrane's selectivity and faces the catholyte. The latter is more conducive and contributes to its mechanical strength. Reinforcing fibers located in the sulfonic layer make it even stronger [25].

A previously treated saturated brine solution is fed to the anodic compartment, while demineralized water is fed to the cathodic compartment. Ideally, the membrane allows sodium ions and associated water to pass through (Figure 5). Several percent of the hydroxide ions produced at the cathode actually pass through the membrane and into the anolyte which is the fundamental cause of current inefficiency. Chloride ions in parts-per-million (ppm) quantities pass through into the catholyte. The anolyte contains unreacted sodium chloride and other inert ions. Usually, 30 to 32% caustic soda is fed to the cathode compartment, where sodium ions combine with hydroxyl ions formed by the electrolysis of water molecules. This produces more caustic soda, raising the concentration of the solution to 32–35%. The water-saturated hydrogen gas exits the catholyte compartment.

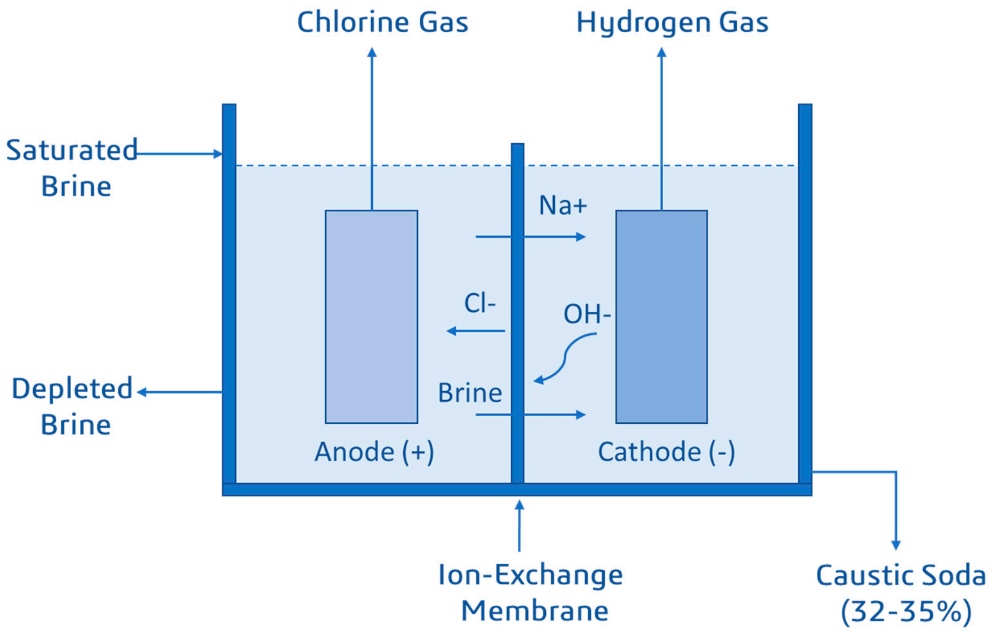

Figure 5. Membrane cell techniques (cell level) [5].

In the product recovery stage, a portion of the caustic soda product withdrawn from the cathode compartment is taken off as a product. The remainder is diluted and returned to the cathode compartment. The complete processing of chlorine gas involves converting a hot, moist vapor that is roughly at the same pressure as the atmosphere into a cold, dry liquid subjected to a large amount of positive pressure. Hence the common processing steps are cooling, drying, compression, and liquefaction [5].

4. Opportunities Chlor-Alkali Industry Derived By-Products in Bangladesh

The by-products of chlor-alkali process, e.g., Cl_2 and H_2, have numerous applications. Previously, we have mentioned the production of PVC from the chlor-alkali-derived Cl_2. On a global scale, PVC is the third most widely manufactured synthetic polymer. The wide range of applications, e.g., electronics, automotive components, building materials, and packaging, increases its demand worldwide. Sixty percent of total pipes and fittings use PVC as a construction material [13]. In most commodity plastics, the main components are carbon and hydrogen, whereas PVC also contains chlorine, which allows PVC to be compatible with a wide range of other materials, making PVC a particularly versatile material [28].

In the first step of PVC production, ethylene (natural gas derivative) is separated from natural gas or petroleum by thermal cracking. The liquid petroleum is fed into the steam furnace at high pressure which creates changes in the molecular weights of petroleum constituents. The ethyne is then identified, segmented, and cooled to a liquid. The Cl_2 manufacturing process involves a common chemical reaction: electrolysis. Electricity is applied to seawater or industrial-grade salt solution (brine). The applied electricity causes electrons to flow from the anode to the cathode of the cell containing brine. The overall reaction is:

$$NaCl + H_2O + \text{electricity} \rightarrow NaOH + Cl_2(g) + H_2(g)$$

In the positively charged anode, the negatively charged chloride (Cl^-) ions lose two electrons ($2Cl^-(aq.) \rightarrow Cl_2\ (g) + 2e^-$) and instantaneously the Cl_2 is formed.

Then, the ethylene and Cl_2 are reacted to form ethylene dichloride (EDC). After that, EDC passed passes through a catalytic thermal cracking process, that produces vinyl chloride monomer (VCM). The VCM is then fed into the catalyst-reactor for polymerization for linking of VCM molecules and finally produces PVC resin. The overall process is illustrated in Figure 6.

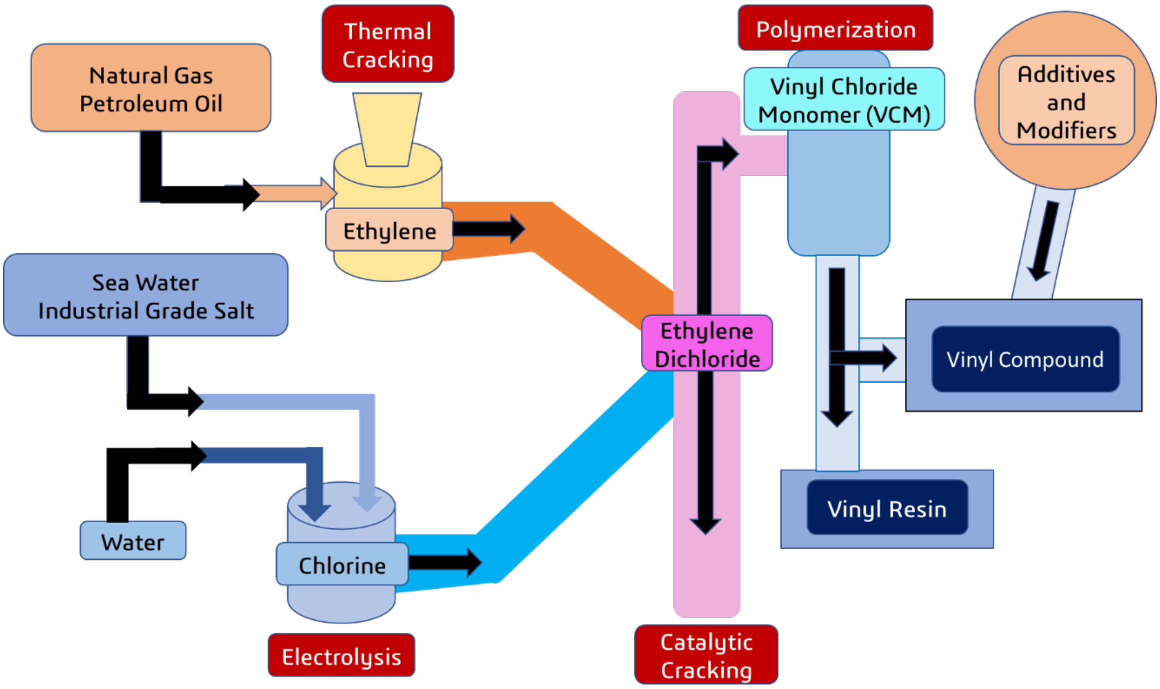

Figure 6. The generalized production process of vinyl resin [29].

In Bangladesh, the first stage of the PVC production process combines ethylene (excluding the NG cracking process, as PVC plants import ethylene as raw material) and Cl_2 to produce ethylene dichloride, which is then converted into vinyl chloride (the basic building block of polyvinyl chloride or PVC). The polymerization process joins the vinyl chloride molecules to form PVC chains. The PVC produced in this manner is a white powder. PVC is combined with other ingredients to create formulations for a variety of products [10].

In Bangladesh, the usage of plastic items is expanding with the development of the country, and plastic consumption has increased by 10% in household products and by more than 20% in general products during the last few years. In Bangladesh PVC, a high-strength thermoplastic is utilized in a broad range of products, from pipes to fittings to wires and cables to bottles to profiles to hose and tubing; its demand has gradually been on the rise in the domestic market. After meeting the domestic demands, a significant portion of the locally manufactured plastic products is exported abroad [30].

Due to increased demand for the material in current government development projects and modern water supply, sewerage, and irrigation systems, the domestic PVC pipe manufacturing industry is expanding at a rate of almost 20% per year. Bangladesh used to satisfy 90% of its pipe demand through imports from China, India, Malaysia, and other nations two decades ago. However, the situation has improved significantly since extremely high-quality pipes are now manufactured locally. As a result, around 700 million USD worth of PVC pipes were sold in 2020, with prominent market players such as RFL Plastics, Dhaka, Bangladesh, National Polymer, Gazipur, Bangladesh, Lira, Dhaka, Bangladesh, Gazi, Dhaka, Bangladesh, Anwar Polymer Industries Ltd., Mymensingh, Bangladesh and Bengal Plastic, Dhaka, Bangladesh meeting 80 percent of demand [31]. A total of 40 firms and 16,000 people are involved in this industry at present. Among the domestic PVC pipe manufacturers, RFL Plastics is the frontrunner, having the largest supply chain [32]. The volume of various types of PVC bags manufactured has increased in recent years. After meeting domestic demand, a significant portion of these products is exported. At present, investment in this sector totals 765 million USD, and the industry is growing at a 20% rate. Around 100 firms manufacture these bags in Bangladesh, with Deshbandhu Polymer Limited, Dhaka, Bangladesh and Khan Brothers PP Woven Bag Industries Ltd., Dhaka, Bangladesh being among the market's leading players [32]. The pandemic had a significant impact on the PVC-based industries in Bangladesh and exports decreased for the majority of companies. Following the pandemic's second wave, the global economy reopened and demand for industrial products increased exponentially. As a result, manufacturers received additional purchase orders, and the industry is growing steadily once again. Therefore, the future market of PVC in Bangladesh is booming. However, each year Bangladesh imports a huge amount of PVC resin to meet the domestic demand. There are no PVC industries in Bangladesh except the Meghna PVC, which has not started production yet. The raw material Cl_2 of the PVC production process is produced by brine electrolysis. The brine, electricity, and maintenance cost of an electrolysis unit increases the price of PVC resin. For an efficient process, the chlor-alkali-derived Cl_2 can be directed to PVC production to meet this demand and cut the cost. The integration process of chlor-alkali and PVC industries is shown in Figure 7A.

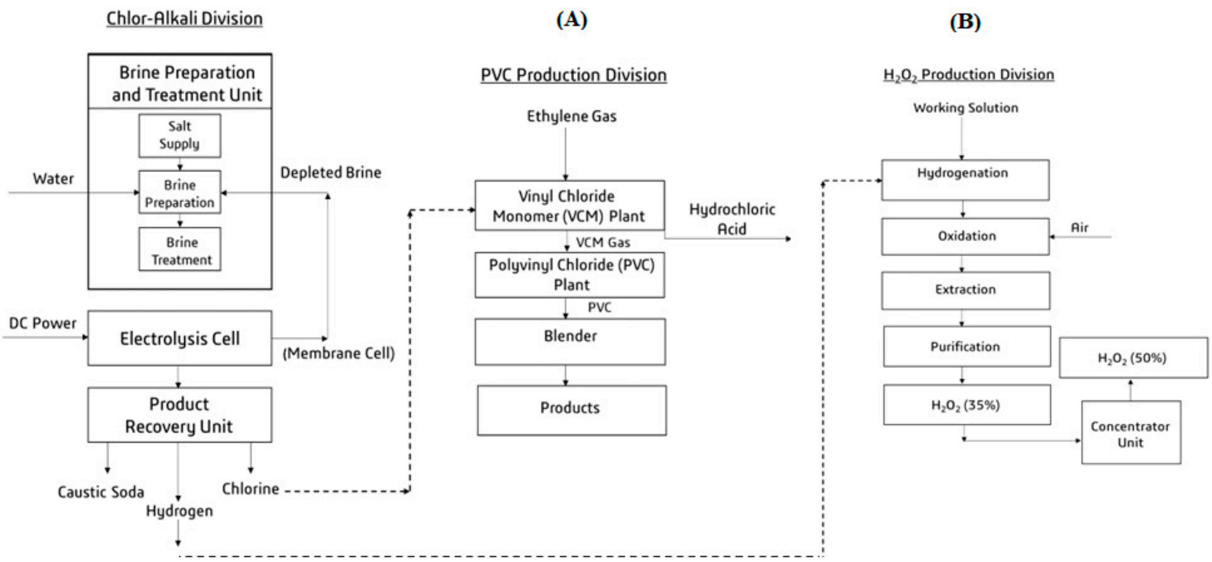

Figure 7. Combined Process Flow Diagram of Chlor-Alkali Process and PVC Processing Using Chlorine (**A**) and Integration of Chlor-Alkali Process and H_2O_2 production Unit (**B**).

In different parts of the world, chlor-alkali plants are located together with PVC plants that use the gaseous Cl_2. The consumer of gaseous Cl_2 (PVC unit) has a direct pipeline to the producers (chlor-alkali unit). Shin-Etsu Chemical Co., Ltd., one of the biggest PVC manufacturers in the world has integrated chlor-alkali and VCM plants. In 2020, Abu Dhabi National Oil Company (ADNOC), Abu Dhabi, United Arab Emirates and Reliance Industries Ltd., Mumbai, India signed an agreement for the establishment of an integrated chlor-alkali and PVC production facility. An integrated plant with 940,000 MT/y chlor-alkali, and 360,000 MT/y of PVC will be built within 2030. Experts suggest that the triggering demand for PVC is going to rebalance the sustainability imbalanced in chlor-alkali industries.

In a chlor-alkali plant, 40% of total electricity consumption for a membrane cell electrolysis process accounts for the generation of H_2 [33]. The chlor-alkali industries of Bangladesh vent the H_2 as waste to the air; therefore, 40% of the cost of electricity is being wasted in these Bangladeshi chlor-alkali industries. An integrated system should be established in Bangladesh to utilize the vented H_2 of chlor-alkali plants. However, the potential applications of H_2 can be categorized into three groups, e.g., industrial feedstock, power generation, and transportation fuel [14]. H_2 is one of the feedstocks of ammonia, steel, hydrogenation, hydrocracking, and synthesis gas production unit. In Bangladesh, ammonia production is based on natural gas (NG). However, the shrinkage of NG reservoirs leads to a low production capacity for ammonia and urea industries. The enormous demand for ammonia and urea in Bangladesh cannot be satisfied by the chlor-alkali-derived H_2. The H_2 utilization in the hydrogenation unit of the hydrogen peroxide (H_2O_2) production unit is a common practice in Bangladesh [34]. In Bangladesh, Tasnim, Samuda, ASM, and HP chemicals, etc., are the leading manufacturers of H_2O_2. The demand for H_2O_2 (35%) and H_2O_2 (50%) in Bangladesh in total is 450 MT/day, while the production capacity is only 218 MT/day [35]. Bangladesh imports H_2O_2 from Thailand, South Korea, India, Japan, and the Netherlands. However, the utilization has not reached its optimum state, therefore the integration of chlor-alkali and H_2O_2 production unit has to be established. The H_2 of chlor-alkali industries has to be collected with proper regulations and supplied to the hydrogenation unit of the H_2O_2 production division (Figure 7B), which will significantly reduce the cost of the process.

The wasted H_2 can also be utilized for power and heat generation. The power can be scaled in grid power and the heat can be used in the industries for process heat supply. As H_2 production accounts for 40% of the electricity use in the chlor-alkali process, the use of H_2 as an alternative clean fuel with a low additional cost can be of great benefit to the industry [36]. A study based in Jordan reported utilizing 43% of the total H_2 production of a chlor-alkali plant by installing a hydrogen boiler next to the existing fuel boiler to produce steam for process heat production. Of the total steam requirement, 34% was supplied by this process, which in return yields a saving percentage of 33.37% and a payback period of 0.947 years. The process of steam production from H_2 of chlor-alkali industries achieved major savings on fuel usage and expenditure, as well as, major reductions in CO_2 emissions (reduction of 910 MT/y) [33]. Production of H_2 fuel cells for transportation and power plant systems has unveiled its highest potential. The fuel cell electric vehicle (FCEV) has become very popular in recent years. Fuel-cell electric vehicles (FCEVs) can substitute internal combustion engine (ICE) vehicles, e.g., buses and trucks, in the transport sector. Total FCEV stocks are targeted to reach 1.0 million in 2030, 1.3 million in 2035, and 5.0 million in 2050 [37].

China has shown its interest in the H_2 fuel cell power plant technology based on chlor-alkali waste H_2. The byproduct H_2 reacts with O_2 and the energy is converted into electricity. In the fuel cell, pure water and heat are also formed. The generated electricity and heat can be reused in the chlor-alkali plant, which would a sustainable solution with a lot of economic profit [33]. MTSA Technopower B.V., Arnhem, Netherlands as established a 2-Megawatt (MW) fuel cell power plant in a chlor-alkali plant at Yingkou, China [38]. Previously, MTSA Technopower in Arnhem, the Netherlands, started small-scale hydrogen powerplants of 4 Kilowatt (KW) backup systems [39]. In Bangladesh, H_2 recovery can be accomplished by an alkaline fuel cell and H_2 boiler techniques. The alkaline fuel cell for electricity and H_2O production and hydrogen boiler for steam generation can be feasible solutions. For chlor-alkali plants (high purity H_2 is available as a byproduct) the utilization of an alkaline fuel cell system can be a viable solution for H_2 recovery. In addition, H_2 boiler systems can generate half of the steam needed in a chlor-alkali plant [40]. However, in this study, we have prioritized the chlor-alkali and PVC integration approach to utilize the gaseous Cl_2. With the advancement of technologies, Bangladesh can unveil the other potential of H_2 from chlor-alkali plants as well.

The sustainable utilization of Cl_2 and H_2 of chlor-alkali plants clearly aligns with several points of Sustainable Development Goals (SDGs) (Figure 8). If Bangladesh utilizes the chlor-alkali derived Cl_2 in the PVC plant, the water pollution by the chlor-alkali industries with its chlorinated products would be reduced, which will accomplish objective 6 (clean water and sanitation). The H_2-based energy production facility from the by-products can address goal 7 (affordable and clean energy). The integration process would be an excellent example of goals 9 (industry, innovation, and infrastructure) and 10 (responsible consumption and production), respectively.

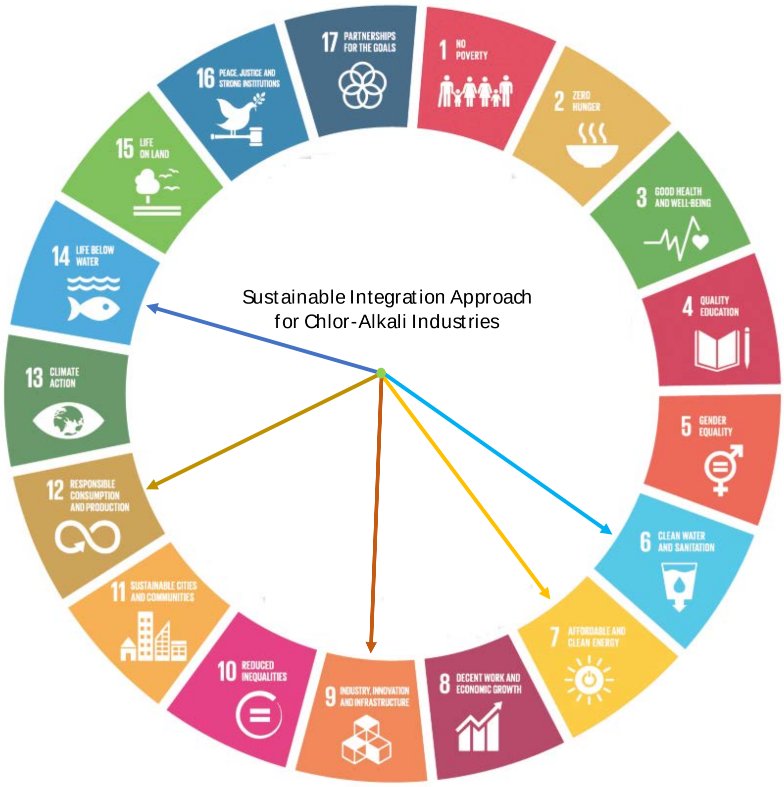

Figure 8. Specific goal addressing of SDGs by sustainable chlor-alkali industry integration [41].

5. Case Study in Bangladesh

In Bangladesh, Chlor-alkali plants dispose of a huge quantity of Cl_2-based products in the water bodies. In the near future, the diversity of living creatures would experience a drastic extinction due to the hazardous nature of Cl_2, if the uncontrolled disposal is not systematically controlled. Therefore, immediate corrective action should be taken for the proper disposal of Cl_2 by the government and the local authority. Table 2 represents the nameplate production capacity (caustic soda, Cl_2, hydrochloric acid, sodium hypochlorite, stable bleaching powder and chlorinated paraffin wax) of GHCL, ASM, Samuda, Tasnim and SR chlor-alkali industries.

Table 2. Production capacity of different chlor-alkali plants in Bangladesh.

Product Name	Production Capacity, MT/d						Yearly Production, MT/y
	GHCL	ASM	Samuda	Tasmin	SR	Total	
Caustic Soda (98% basis flake/liquid)	70	65	200	430	90	855	282,150
Chlorine (Cl_2) gas from Electrolyzer	62	58	178	382	80	759	250,470
Hydrogen production	1.75	1.63	5	10.75	2.25	21.38	7055
Chlorine (Cl_2) liquid	10	10	20	30	15	85	28,050
Hydrochloric Acid (32% HCl)	220	200	180	400	200	1200	396,000
Sodium Hypochlorite (NaOCl)	10	10	30	30	-	80	26,400
Stable Bleaching Powder (SBP)	15	20	16	-	-	51	16,830
Chlorinated Paraffin Wax (CPW)	10	20	20	15	-	65	21,450

In modern engineering, PVC serves the versatility to meet the necessary criteria, e.g., high impact strength, extrudability, low-temperature resistance, and low reactivity. In addition to new project development, PVC is widely used in refurbishment, where it replaces traditional materials, e.g., metals and wood. In Bangladesh, different renowned companies sell PVC products, e.g., pipes, doors, windows, and fittings. The ongoing government development projects, modern water supply systems and state-of-art-technologies in agriculture boosted the demand for PVC in Bangladesh. However, the locally established companies captured the PVC market in Bangladesh. Table 3 and Figure 8 summarize the Bangladesh market status of PVC in terms of selling PVC products, e.g., pipes, doors, and fittings (the data were collected from a local industry).

Table 3. PVC materials market scenario in Bangladesh.

Company Name	PVC Pipe Sell	PVC Door Sell	PVC Fitting Sell	Total
	(Million USD)/y			
RFL	144	69	30	243
Gazi	66	16	17	99
Npoly	24	7	6	37
Akij	20	0	7	27
Navana	18	0	6	24
Bengal	25	0	4	30
Partex	10	52	3	65
A1 Polymer	32	0	8	41
N Mohammad	0	16	0	16
Royal Plastic Ltd.	11	10	6	27
Lira	17	11	4	32
Local Non-Brand	72	32	21	126
	Total			765

Table 3 and Figure 9 represent the PVC materials sells (million USD/y) and cumulative market capture (%) of different reputed and local vendors. The RFL group is the leading market holder in Bangladesh with a sell worth 243 million USD/y (31.6% of the total volume). Gazi group and Partex sell 99 million USD/y (13.2% in volume) and 65 million USD/y (8.5% in volume), respectively.

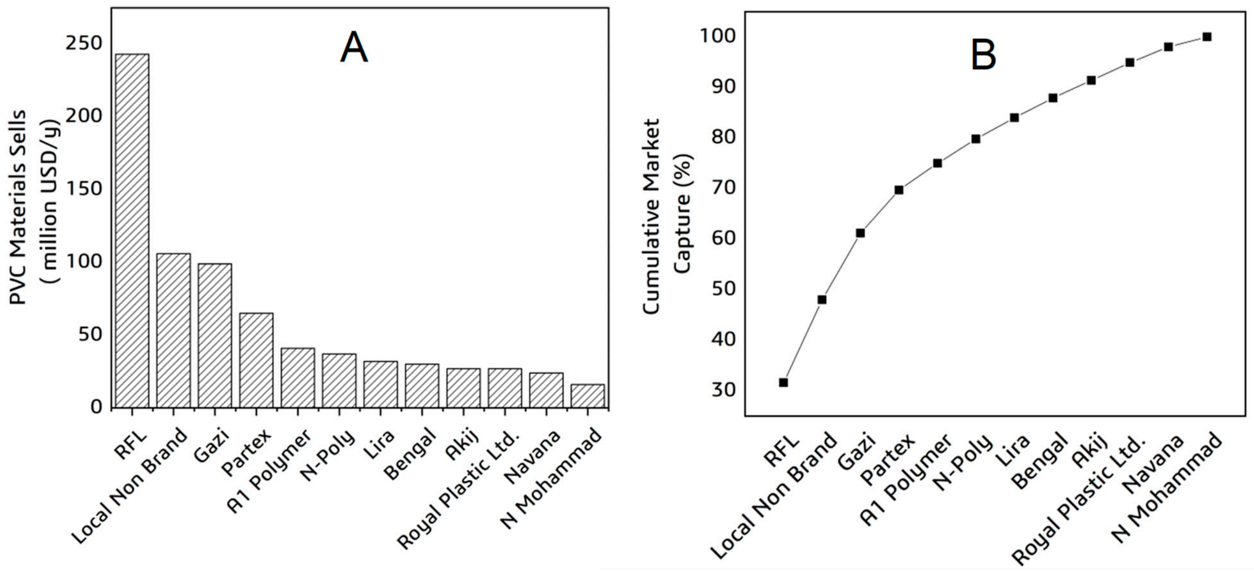

Figure 9. PVC materials sales (**A**) and cumulative market capture in Bangladesh (**B**).

Currently, there are no PVC manufacturers in Bangladesh. Meghna PVC would complete the performance-guarantee test (PGT) and initiate production by the end of 2022. In this section, an integrated approach to chlor-alkali and PVC industries will be portrayed from Bangladesh's perspective.

5.1. Economic and Environmental Sustainability Prospect in Bangladesh

The chlor-alkali process is characterized by a high level of energy consumption and environmental pollution all over the world. Gaseous Cl_2 and H_2 are the by-products of chlor-alkali industries [30]. The underutilized waste streams cause huge environmental pollution and incur a huge energy consumption. Due to the toxicity of Cl_2, the chlor-alkali industries of Bangladesh convert it to liquid Cl_2, HCl, NaOCl, SBP, and CPW. However, the conversion process is not feasible in terms of economic and environmental aspects. Bangladesh needs a master plan to utilize the Cl_2; PVC industries are the best choice in this scenario. A private company named 'Meghna PVC' has initiated PVC resin production based on imported ethylene ($H_2C{=}CH_2$) and Cl_2. In developed countries, the PVC industries use natural gas (NG) cracking units for $H_2C{=}CH_2$ production. However, the NG reserve in Bangladesh is shrinking, thus there is no alternative for $H_2C{=}CH_2$ import. However, for Cl_2, the PVC industries of Bangladesh can utilize chlor-alkali. They can use the gaseous Cl_2 from GHCL, ASM, Samuda, Tasnim and SR. The integration approach would decrease the cost of Cl_2 import, unnecessary extra conversion of gaseous Cl_2 and environmental pollution. The transportation facilities of Cl_2 from chlor-alkali production unit to the VCM plant will depend on several factors, e.g., distance, flow rate, weather condition, temperature variation, piping space, and safety concerns [42]. The subsequent subsections present the calculations, prospects, environmental viability, and challenges of the integration process.

The systematic calculations for PVC-material-based companies in Bangladesh are presented in Table 4. The calculations depict the imported PVC resin amount and the calculated PVC resin cost is nearly equivalent in Bangladesh.

Table 4. Estimated Calculation for PVC Companies in Bangladesh (Calculation was made based on collected data from local sources).

Serial Number	Context	Money, USD
01	The worth of imported PVC resin/y	330 million
02	Per MT PVC resin price	1180
03	Total PVC materials sell/y	768 million (Table 3)
04	Cost of PVC resin (43% of PVC materials cost)	(768 × 0.43) million = 330.24 million

Meghna Group, Bangladesh is constructing a PVC plant with a production capacity of 150,000 MT per year, which will use 48% ethylene ($CH_2 = CH_2$) and 52% Cl_2 as raw materials for the production of 150,000 MT of PVC. Table 5 summarizes the calculations for the PVC plant.

Table 5. Calculations for Meghna PVC plant Cl_2 consumption.

Serial Number	Context	Quantity (MT)
01	PVC plant capacity	150,000
02	Cl_2 required (52%) for PVC production (Cl_2 consumption)	(150,000 × 0.52) = 78,000
03	Produces Cl_2 per year	250,470
04	Residual Cl_2	172,470

Therefore, the PVC plant can utilize 45.2% residual chlorine for their PVC production by integrated gas-supply lines or gas transportation systems which would be a great approach to economic and environmental aspects. Every year Bangladesh imports 280,000 MT of PVC resin worth 330 million USD/y (Table 4). The amount of Cl_2 required is 145,860 MT/y. Bangladesh earns 768 million USD/y based on 280,000 MT PVC consumption/y. Therefore, each MT Cl_2 consumption will earn a revenue of 0.005265 million USD. The residual Cl_2 can earn revenue of 908 million USD/y, which can also save money on PVC resin and ethylene import costs [40].

The serious adverse health and environmental effects of Cl_2 and chlorinated compounds of chlor-alkali industries have raised consciousness in recent years. Bangladeshi chlor-alkali industries convert its gaseous Cl_2 to HCl, NaOCl, SBP, NH_4Cl, and CPW with the major contribution HCl and NaOCl. Figure 10 presents the demand and supply bar chart of PVC, HCL, and NaOCl in Bangladesh. In Bangladesh, every year 259,125 MT of HCl is wasted and discharged to river water containing 80,681.2 MT of Cl_2. The disposed HCl acidifies river water by reducing the pH value. On the other hand, sodium hypochlorite (NaOCl) is produced at 26,400 MT/y, of which 18,980 MT/y is used and the rest of the NaOCl is discharged into the river water. The NaOCl when added to water, it forms an OCl^- (hypochlorite) ion that is called free chlorine and dissolves in water. Two substances are formed that play a role in oxidation and disinfection [43]. These are hypochlorous acid and the less active hypochlorite ion. The pH of the water determines how much hypochlorous acid is formed. HCl and NaOCl in river water can lead to influence aquatic biota at all levels of the food chain, from primary producers, such as aquatic algae and macrophytes, to macroinvertebrates, fish and even water birds [44]. Overall reduction in species biodiversity as well as functional diversity. Aquatic animals (invertebrates and fish) will be vulnerable due to increased hydrogen ions and changes in food availability and quality [45]. The growth of some plants may be affected by the reduced availability of dissolved inorganic carbon, macronutrients such as phosphorus, and changes in interspecific competition. Chlorinated organic compounds, or 'organochlorines', are toxic, bio-accumulative and the cause of problems such as cancer, immune suppression, birth defects, fertility problems and endocrine disruption [46]. The chlor-alkali industries should design a chlorine destruction unit to absorb the cell evaluated Cl_2 in the event of a process upset until the plant can be shut down to prevent the gaseous Cl_2 emissions [26]. The chlor-alkali industries have to ensure no systematic discharge of NaOCl and HCl to water bodies. Minimizing the discharge of oxidants, chlorate and bromate has to be ensured [22].

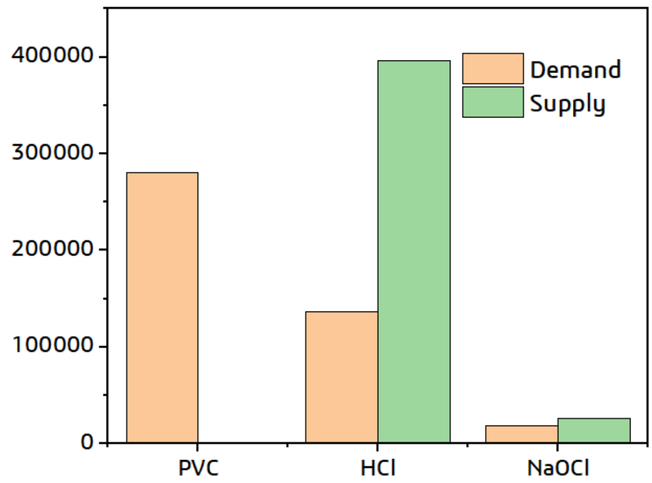

Figure 10. The demand and supply of PVC, HCl, and NaOCl in Bangladesh.

The actual impact of the integration process in terms of economic, energy, and pollution perspectives can hardly be assessed. The feasibility studies with detailed market analysis and installment of a pilot plant can give us a proper view of the integration approach. However, Fang Wang et al. reported the integrated sustainability assessment of integrated chlor-alkali and PVC chains in China [47]. The production chain is dependent on the environmental, energy, and economic aspects. They have evaluated the production chain of the integrated chain by driving the force–pressure–state–impact–response (DPSIR) framework and system dynamics (SD) models and explored the interactions among the environment–energy–economic systems of the process. To establish the DPSIR model, they developed an evaluation indicator and categorized it into three segments, e.g., target, component, and indicator level. Sustainability was set as a target, whereas pressure, state, impact, and resources were selected as the driver. The SD model was developed by iteration by software Vensim PLE. Three subsystems, e.g., energy, economic, and environment were selected and studied extensively. After that, different scenarios, e.g., business-as-usual (current development conditions without any extra policy implementation), resource recycling, energy utilization, structural adjustment, and sustainable development were scrutinized. The integrated approach developed by the study can be applied in general to provide decision support for developing corporate strategies to achieve sustainable development. The results show that the sustainable development scenario showed reductions of 52% in energy intensity and 88% in chemical oxygen demand load intensity compared to the business-as-usual model. Therefore, in Bangladesh, we need to change the current process of the non-integrated chlor-alkali process and have to introduce proper policies for the successful establishment of chlor-alkali and PVC intensification.

5.2. Cl_2 Transportation Challenges in Bangladesh

Figure 11 shows the location of the studied chlor-alkali industries in Bangladesh. The sites of the plants are highly scattered and unplanned for the feasible integration approach. We have categorized the study area into three sections, e.g., 1, 2, 3 (Figure 11). Area 1 consists of the Meghna PVC industry (for model development), Tasnim, and Samuda Chemical complex. Area 2 consists of ASM and GHCL, whereas area 3 includes only SR chemicals. The transportation of gaseous Cl_2 is crucial for successfully integrating the chlor-alkali and PVC industries. Gaseous Cl_2 can be transported through a long-distance pipeline or safeguarded vessel truck with the satisfaction of design and operating conditions [48].

The formation of condensate in gaseous Cl_2 transport pipelines is challenging for chemical industries [49]. Gaseous Cl_2 may expand, cool, and be partially condensed. To prohibit the phenomenon, regulated electric heat traced and insulated pipelines should be considered. Pressure control or regulating valves in the pipelines or vessels have to be incorporated. Leakage prohibition and appropriate diameter should be considered for the pipelines [50]. The route for a pipeline has to be selected with special consideration to environmentally sensitive areas and avoid the populated area. The minimization of public access as much as possible while routing a pipeline is necessary. Consideration should also be given to potential pipeline damage due to adjacent pipelines, soil conditions, traffic, vandalism, and other factors along the route. Before the start-up, EIA, RA, QRA, HAZOP, HAZID study, and HAZAN study for the pipelines are necessary [51]. Therefore, from areas 2 and 3, transportation of gaseous chlorine to the PVC plant is not feasible. Tasnim Chemicals is within a 0.4 km radius of Meghna PVC, which implies pipeline transportation of gaseous Cl_2 from Tasnim to Meghna PVC is possible. Samuda Chemicals is within about a 10 km radius; therefore, pipeline and vessel (chilled and compressed Cl_2) transportation both have to be evaluated, providing the safety and economic aspects. Transportation of compressed Cl_2 from ASM Chemicals and GHCL (nearly 40 km) through a vessel would be more feasible. Vessel transport by facilitated and safeguarded trucks can be considered. SR chemical is situated very far from Meghna PVC (200 km); here the authority needs to take necessary steps regarding transportation. However, Tasnim Chemicals itself produces 126,000 MT gaseous Cl_2/y and the Meghna PVC requires only 78,000 MT Cl_2. In this context, integration of Meghna PVC is not feasible with other plants. Therefore, another PVC plant has to be set up for the sustainable integration of chlor-alkali and PVC industries in Bangladesh.

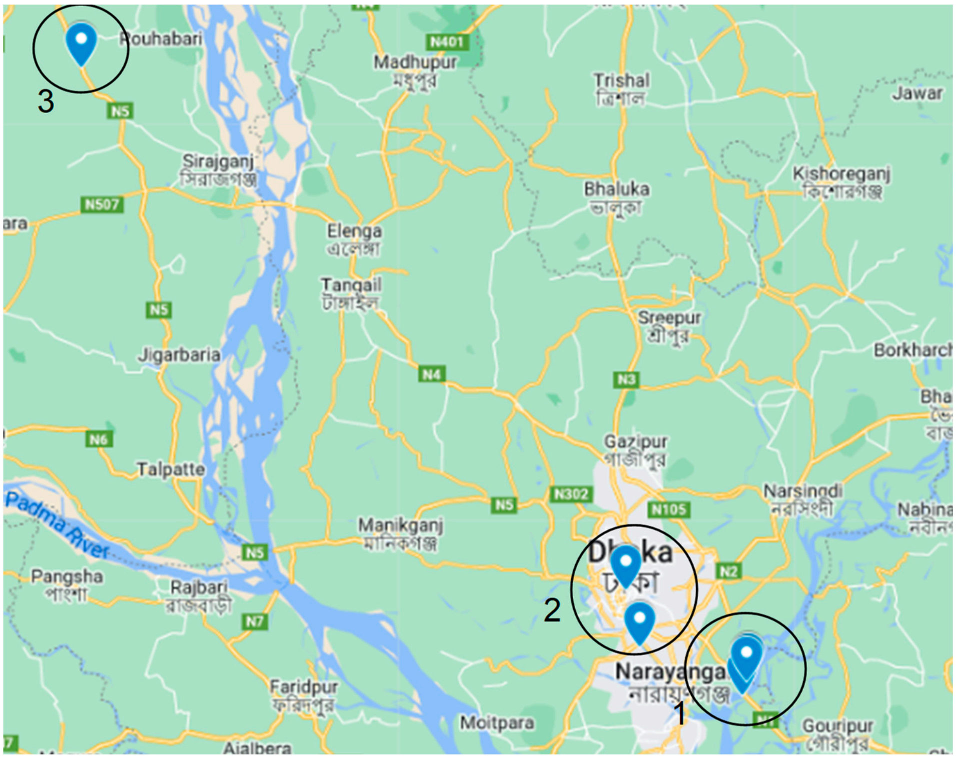

Figure 11. Area-based categorization of the studied plants [52].

6. Conclusions

We investigated the opportunity that chlor-alkali industries provide in terms of utilizing its by-products such as Cl_2, and H_2 for the production of other chemicals that a specific country may require. The prospects of the chlor-alkali-derived Cl_2 for PVC production and H_2 for H_2O_2 and energy production have been critically analyzed. We provided a detailed and in-depth analysis in the context of Bangladesh, which can be easily tailored for other countries worldwide having chlor-alkali industries. The membrane cell electrolyte process was thoroughly studied to understand the chlor-alkali process. The opportunities for Cl_2 and H_2 were systematically scrutinized. Our investigation shows that the gaseous Cl_2 processing demand in Bangladesh is 68,779 MT/y, and the remaining Cl_2 is converted to chlorinated chemicals and discharged into the environment by the end of its life. For the sustainable development of the chlor-alkali plant in Bangladesh, appropriate planning is required to utilize the chlor-alkali-derived Cl_2. The PVC pipe and other PVC materials demand is increasing, and therefore, an integrated approach of chlor-alkali and PVC industries can ensure the proper utilization of Cl_2. The GHCL, Samuda, ASM, Tasnim, and SR use the membrane cell electrolytic processes that produce 250,470 MT/y gaseous Cl_2 of which 68,779 MT/y Cl_2 is consumed for the production of liquid Cl_2, HCl, SBP, CPW, NaOCl, etc. A 150,000 MT/y PVC industry will be established by the end of this year, which can utilize only 78,000 MT of Cl_2. The chlor-alkali industries can adopt the Cl_2 utilization concept by integrating PVC plants nearby to cancel out the Cl_2 transportation challenges. The utilization aspect of H_2 for H_2O_2, electricity production, or fuel cell-assisted vehicles can increase the self-sustainability of chlor-alkali plants. The establishment of power plants based on waste H_2 can benefit Bangladesh to deal with the increasing energy demand of electricity and scarcity of natural gas. The sustainability of the integrated approach in terms of economic, energy, and environmental aspects should be analyzed by different frameworks and simulation models. Overall, the paper serves as the initiation approach for sustainable chlor-alkali and PVC industry integration and the use of clean hydrogen fuel not only in Bangladesh but anywhere in the world.

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