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Review Article

REVIEW ON THE DIFFERENT PROCESSES OF UREA PRODUCTION FOR ACHIEVING SUSTAINABLE DEVELOPMENT GOALS IN NEPAL

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ABSTRACT

Infrastructural development in agriculture will directly help achieve sustainable development goals (SDGs) in the least developed countries (LDCs) as the majority of the population in these regions depend on agriculture. This study presents the case of Nepal, one of the LDCs and suggests the establishment of a urea manufacturing plant for improving agriculture productivity and fulfilling the SDGs of zero hunger, no poverty and decent work, and economic growth. Herein, in the context of Nepal, we have reviewed: (i) the status of SDGs of Nepal, (ii) agricultural productivity associated with usage and supply of urea, (iii) technologies associated with urea production, (iv) the feasibility of establishing a urea plant based on the raw material availability and sustainability and (v) the opportunity for economic and technological development. The hydropower-powered electrolysis and CO_2 capture from cement industry flue gas were determined to be the strategically feasible and sustainable pathway for urea production and consequently, the fulfillment of SDGs in the context of Nepal. A detailed project study on the economics of the electrolysis-based urea manufacturing process is recommended to foster a sustainable development national plan for Nepal. Although this report highlights the various aspects of urea production in Nepal, this study can be useful for other LDCs dependent on agriculture to achieve SDGs.

Keywords: Agricultural productivity, CO_2 capture, electrolysis, sustainable development goals, urea

INTRODUCTION

Sustainable development goals (SDGs) were adopted by the United Nations as an initiative to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity (UNDP, 2015). The fulfilment of SDGs is especially vital to the least developed countries (LDCs) as the people in these countries are the least prosperous and the poorest (Kim, 2018). The majority of people in LDCs are involved in agriculture, hence, improvement in the agriculture sector should be focused to stimulate inclusive economic growth and consequently achieve the 'no poverty'; 'zero hunger'; 'good health and well-being'; and 'decent work and economic growth' SDGs (FAO, 2018). Nepal, a least developed country, has 66% of the workforce directly or indirectly employed in agricultural and livestock production (FAO, 2016). Nepal has more than 4120 hectares of arable land, 25% of which is still uncultivated, and a favorable climate of sub-tropical in the plains and temperate in the hilly and lower mountainous region to sustain its population with domestically produced agricultural products and drive an agro-based economy (MoALD, 2020). However, the country relies heavily on food imports and the contribution of agriculture to gross domestic product (GDP) is declining every year. In the fiscal year 2019/20 alone, Nepal imported more than USD 2 billion worth of food, about 20% of the total import (MoF, 2020a, 2020b). The country imports even the most extensively farmed crops such as rice, lentils, maize, and vegetables. The low agricultural output of the country can be partially attributed to the very low use of fertilizers, about 86.9 kg of fertilizer per hectare of arable land (World Bank, 2018). In comparison, the fertilizer use in India, Bangladesh, and Pakistan were 175, 319, and 156 kg respectively per hectare of arable land (World Bank, 2018). The major reason for the low use of fertilizer in Nepal is simply the low and untimely availability of fertilizer during the harvest season as the country has to import fertilizer from neighboring countries. Thus, in order to increase production, drive the economy and subsequently alleviate poverty and achieve SDGs, timely and adequate supply of fertilizer is important. The supply of fertilizer can be addressed by establishing a fertilizer manufacturing plant.

The annual fertilizer demand of Nepal is 800×10^3 metric tons (MT) (B.C. *et al.*, 2020). Urea is the most preferred fertilizer because of its high nitrogen content - a trait very suitable for acidic Nepali soil and rainy climate (B.C. *et al.*, 2020; JICA, 1984). The imports have, however, failed to meet even half of the annual fertilizer demand since the 2015/16 fiscal year (MoALD, 2020; Panta, 2018). Only the state-run Agricultural Inputs Company Limited (AICL) and National Salt Trading Corporation Limited (STCL) oversee the import of fertilizer in Nepal. To mitigate the procurement problem of the previous years, the government for the first time in the fiscal year 2019/20 contracted two private firms to import urea, yet, both the firms failed to import their contracted amount (Panta, 2018). The farmers often purchase fertilizer from informal sources due to these frequent failures to import a sufficient amount of fertilizer (Panta, 2019). The situation was further exacerbated by the recent COVID-19 restrictions: purchase from informal sources was impossible and the demand could not be fulfilled by state and private imports. Thus, the COVID situation has underscored the need for Nepal to establish a fertilizer (urea) manufacturing plant to fulfil the increasing fertilizer demand, increase productivity, ensure food security, and drive Nepal's agrarian economy.

The Nepalese government has studied the possibility to establish urea fertilizer in the past. Japan International Cooperation Agency (JICA) in collaboration with Nepali experts did the first of the two feasibility studies in 1984 (JICA, 1984). The study focused on the electrolysis of water to produce hydrogen. As Nepal did not have sufficient electricity production (only 156 MW) then, the electricity price per unit (KWh) was very high. The study suggested the electrolysis process to be feasible only if electricity was managed at a price lower than 40% of the usual tariff at the time (JICA, 1984). The study concluded that the project was not financially viable and suggested the import of urea from India (JICA, 1984). The second feasibility study was done in 2015 by Infrastructure Development Corporation, Karnataka (iDeCK), India in association with the Institution of Agricultural Technologists (IAT), India, and Shah Consultant International (P) Limited, Nepal under the Office of Investment Board Nepal (OIBN) (OIBN, 2015). The study focused on three major ways to produce hydrogen: burning coal, water electrolysis, and steam reforming of natural gas. The study concluded that the urea plant was feasible as long as natural gas was used as feedstock. Nepal did not extract its natural gas substantially; so, the study recommended constructing the plant on a 400-acre land in Dhalkebar, Dhanusha, Nepal, and procuring natural gas via a pipeline from Jagdishpur, India (OIBN, 2015). The study assumed that the government would import natural gas in a fixed-price long-term deal (fixed at US$ 5.5 per Metric Million British thermal unit (MMBtu) natural gas) and facilitate the delivery (OIBN, 2015).

The JICA report is outdated. Contrary to 1984, Nepal has abundant electricity and is on the verge of generating a surplus. If ongoing 20000 MW worth of projects are completed on time, Nepal is estimated to have more than 3000 MW electricity surplus by 2030 (Thapa & Thapa, 2020). The government, at this time, can also provide electricity at a substantially low rate of USD 0.04 per kW-hr or even lower for the electrolysis plant (Mali *et al.*, 2021). The iDeCK report, on the other hand, fails to take into account the frequent shortages of natural gases and declining natural gas extraction in India since 2011(Kumar *et al.*, 2020; OIBN, 2015). It is estimated that the natural gas reserves in India will be depleted by 2040 and the price of domestically produced gas will double by that time (Kumar *et al.*, 2020). As such, the industrial sectors of India, including the fertilizer industry, are either switching to alternatives like coal gasification or looking to import natural gas via pipeline themselves, which makes a long-term deal at a fixed price uncertain for Nepal (Kumar *et al.*, 2020). To this end, a study by Daayitwa Foundation suggested the feasibility of electrolysis-based urea manufacturing for increasing agricultural productivity (Luitel, 2014).

There are no other studies on the need and the details of the urea manufacturing plant in Nepal besides the above-mentioned three studies. Moreover, the three studies are either outdated or have only explored one pathway for manufacturing urea without considering the changing times and the technologies. In order to fill this gap, this paper aims to review the benefits of a urea manufacturing plant for the country's long-term food security and sustainable economic development. The urea manufacturing facility will also help SDGs of zero hunger, no poverty and decent work, and economic growth. To this end, this study first reviews the status of SDGs in Nepal. Second, this study reviews the current trends in urea fertilizer consumption, government subsidy, and the agricultural output of the country. Third, this study compares the different technologies available for urea manufacture based on the availability of raw materials, the impact on the environment, and the cost of technology. Finally, this paper discusses the opportunities for economic and technological development associated with the set-up of a urea plant. We expect this paper to be helpful to the policymakers in the decision-making process for establishing a urea plant in Nepal with the aim of achieving SDGs.

STATUS OF SDGs IN NEPAL

The government of Nepal (GoN) integrated all of the 17 SDGs into the national development framework in the 15th Five-year Development Plan (2019/20-2023/24). Voluntary National Review (VNR) of the years 2016 to 2019 had highlighted encouraging results; however, the Ministry of Finance (MoF) estimates that COVID-19 restrictions have regressed some of the improvements that the country had achieved (MoF, 2020a; UN, 2020).

The headline goal of the United Nations is to alleviate poverty (SDG 1) by 2030 (UN, 2021). Although absolute poverty declined from 18.7% in the fiscal year (FY) 2017/18 to 16.67% in FY 2019/20, the COVID-19 outbreak is expected to reverse the improvement (MoF, 2020a). The World Bank estimates that up to 100 million people could be pushed back below the poverty line, and almost one-third could be in South Asia, making Nepal a high-risk country for mass poverty (World Bank, 2020). Poverty coupled with soaring food prices is estimated to lower the food supply in poor houses and as a result, cause widespread food insecurity in poor households (World Bank, 2020). Increased food insecurity will aggravate chronic hunger (SDG 2) in countries like Nepal and cause widespread malnutrition among children, which can prove to be catastrophic in the long run (World Bank, 2020). Furthermore, starvation and malnutrition will result in health deterioration and deprive people of good health and well-being (SDG 3) amidst the COVID-strained health care system (Neupane *et al.*, 2021).

Industries (SDG 9) are also expected to be affected by the pandemic. The share of industries in GDP was only about 15.1% against the target of 17.7% in FY 2018/19 (UN, 2020). The manufacturing sector is further expected to experience a negative growth rate of 2.3% in FY 2019/20 (MoF, 2020a). The deceleration in industrial development will further decrease employment opportunities (SDG 8) and widen an already significant gap between demand and supply of labour (MoF, 2020a). Furthermore, it is expected that a large number of Nepali migrant workers will lose their jobs, and about 700,000 will return to Nepal within one year, which will further increase unemployment in the country (UN, 2020). In addition, income and consumption inequality (SDG 10)— which was a challenge even before the pandemic— is expected to worsen because of the COVID-19 restrictions (MoF, 2020a; UN, 2020).

These challenges, which have been even more pronounced in the face of COVID-19, are major obstacles to realizing SDGs by 2030. To this end, the government has identified the need for innovative approaches to accelerate progress in the areas the country is lagging in and create transformative change with a policy of 'Leaving no one behind' (NPC, 2020). The aim is to bring about accelerated economic growth with sufficient employment opportunities for everyone; lift income uniformly across all segments of the population with investment in human capital and infrastructure; and use resources sustainably with proper adaptation to climate change and subsequently achieve SDGs (NPC, 2020). In order to 'Leave no one behind', the government should look to invest in agricultural development as the majority of the Nepali population is involved in the occupation, and any progress in the field will accelerate uniform economic growth and create employment opportunities. Addressing the perennial shortage of fertilizer by establishing a domestic urea plant will ensure major progress in the agricultural sector while simultaneously helping the country achieve SDGs. Table 1 summarizes the possible advantages of establishing a urea plant in terms of achieving SDGs.

Table 1 SDGs and urea plant

Goals	Specific Target	Consequences of Establishing a Urea Plant
SDG 1: No poverty	- All forms of poverty must be eliminated globally	- Substantially increased profitability due to increased productivity for the two-third of the population that is involved in the agriculture sector, resulting in reduced poverty
SDG 2: Zero hunger	- Eliminate hunger and ensure that everyone has access to food - Double small-scale food producers' agricultural production and earnings - Ensure long-term food production systems and resilient farming techniques that boost productivity and output	- Increased agricultural productivity resulting in increased food security and therefore, decreased hunger
SDG 3: Good Health and well-being	- Mitigate maternal mortality to lesser than 70 per 100,000 live births worldwide	- Improved health due to better nutrition intake as a result of increased food security
SDG 8: Decent work and economic growth	- All women and men should be able to find full-time, productive employment and quality jobs - Significantly reduce the proportion of unemployed young people	- Increased productivity and profitability for the sector of the population involved in agriculture - Employment opportunities in the plant and the agriculture sector
SDG 9: Industries, Innovation, and Infrastructure	- Increase access of small-scale industries and other businesses to financial services, particularly cheap financing, as well as their integration into value chains and marketplaces - Improve infrastructure and remodel industries to make them more sustainable by increasing resource efficiency and promoting the use of clean and ecologically sound procedures	- Increased contribution of industries and agriculture to GDP - Decreased trade deficit and less volatile fertilizer market
SDG 10: Reduced Inequality	- Achieve and sustain income growth for the poorest 40% of the population at a pace faster than the national average - Encourage and empower all groups to participate fully in society, the economy, and politics	- Reduced income and consumption inequality due to upliftment of the two-third of the population - Increased employment opportunities for women and other marginalized groups

Targets referenced from (UN, 2021)

AGRICULTURE PRODUCTIVITY AND FERTILISER USAGE

Agricultural productivity

Two third of Nepal's population is directly or indirectly involved in agriculture and livestock production, yet Nepal has a low yield of major crops compared to other South Asian countries and is dependent on imports to meet the demand (Dev, 2013). In terms of cereal yield, Nepal used to be at the top among South Asian nations around 1960—with the yield 198% higher compared to Bangladesh and 212% higher than that of Sri Lanka (Shrestha, 2018). The country was self-sufficient in the food grains till 1980, however, the productivity dropped far below the total demand afterwards with a significant increase in the import of food (Chemjong & KC, 2020). Nepalese agriculture was mainly labour-intensive, so the productivity decrease is partially attributed to the shift of Nepalese youth to other sectors of employment (Satyal, 2012). The decrease in agricultural yield has also contributed to food inadequacy and malnutrition in Nepal. As per the Food and Agriculture Organization (FAO), about 54% of Nepal's total population faced chronic food insecurity in 2014 (FAO, 2016). Nepal imported about 590×10^3 MT of rice worth 199.99 million USD in the year 2016-17 equivalent to 11% of the rice produced in the country (MoALD, 2020; Pudasainee *et al.*, 2018). For context, Nepal once used to export rice with the largest export of 63.5×10^3 MT recorded in the year 1978-79 (Pudasainee *et al.*, 2018). Figure 1 shows the paddy, wheat, and rice productivity of Nepal from the year 2010 to 2019 which demonstrates the lack of increase in agriculture productivity. The productivity has not seen substantial improvement despite improved seed quality under the government's National Seed Vision program and modernized and expanded irrigation facilities. To this end, the adequate supply and the use of fertilizer could increase productivity to keep up with the increased consumption and population growth. One study by the Nepalese government found that the increase in the soil nutrient supply (from fertilizer) to 131 kg/ha by 2017 could increase productivity by 64% to 75% (Paudel & Rago, 2017). Approximately, 310 kg/ha of plant nutrients are estimated to be lost annually due to the cereal-based agricultural system, yet Nepal's fertilizer usage was only 67 kg/ha in 2017 which is far short of the national target and the annual nutrient lost by the soil (Kharal *et al.*, 2018). Thus, the adequate and timely supply of fertilizer during the harvest season could help increase the productivity to keep up with the increasing national consumption and ensure food security.

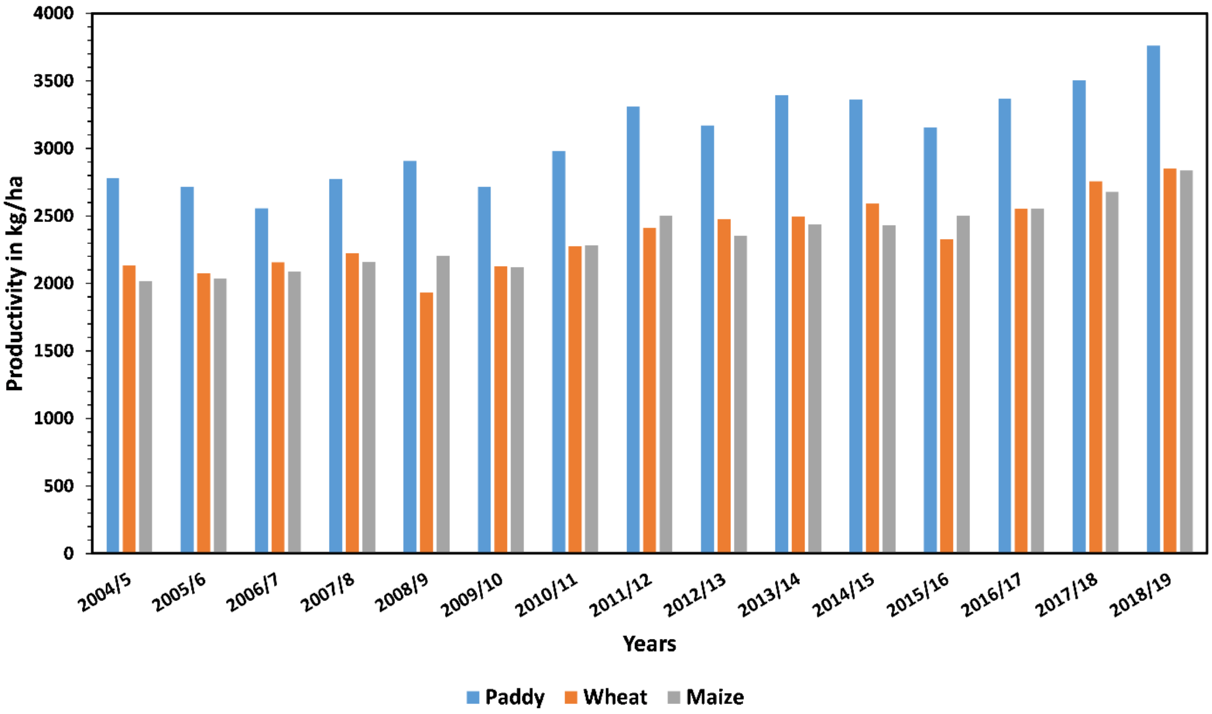

Figure 1 Annual productivity of major cereal crops of Nepal (MoALD, 2020)

Fertilizer Demand and Supply

Fertilizer import in Nepal can be traced back to the 1950s when demand used to be very minimal. Private traders used to procure fertilizers from India and Russia up to the mid-1960s. Agricultural Inputs Corporation (AIC), a government-owned agency was formed in 1966 for the further distribution and importation of fertilizer in the country. The government introduced fertilizer subsidy in 1973 after the price hike of fertilizer in the international market by implementing the Subsidy Policy (1973/74-

1996/97) (B.C. *et al.*, 2020). However, the government could not sustain the financial burden due to the increasing fertilizer demand and the price in the international market. As a result, AIC failed to import and distribute fertilizer according to the demand and the government eliminated subsidies on non-urea fertilizers in 1997 and on urea in 1999 (Bista *et al.*, 2016). The deregulation policy (1997/98-2007/08) was implemented to bring reforms in import and distribution and to encourage private sectors for the smooth supply of fertilizer in the country. Deregulation policy largely failed to bring the expected improvement in supply and import because of the price hike in the international market and fertilizer available at cheaper prices from informal sources along the border (Panta, 2019). The government reintroduced the subsidy scheme in 2009 after many other sequential policies failed to fulfil the fertilizer demand of the country (B.C. *et al.*, 2020; Bista *et al.*, 2016; Panta, 2018). Fertilizer subsidy was introduced to improve the supply situation, increase agricultural productivity, and curb the inflow of low-quality fertilizer from informal sources (Bista *et al.*, 2016). As seen in Figure 2, the fertilizer consumption gradually increased from the lowest sales between 2008/9 and 2010/11. The net supply, however, is still far away from the total annual demand which is 800×10^3 MT (B.C. *et al.*, 2020). Further, it is estimated that the fertilizer import from informal and illegal sources is as much as three times that of the formal supply (Dhakal, 2006).

The subsidy schemes could not bring positive change in the efficient supply of fertilizers and have instead become a big financial burden (see subsidy % in Figure 2) on the government. The fertilizer subsidy was worth 92.04 million USD in the fiscal year 2020/21 alone (MoF, 2020c). The government budget announced recently has allocated a further 100.4 million USD for the fiscal year 2021/22 (MoF, 2021b). The total combined subsidy since 2009 amounts to 577.37 million USD which is around half of the total amount needed to establish an electrolysis-based urea plant in the country (OIBN, 2015).

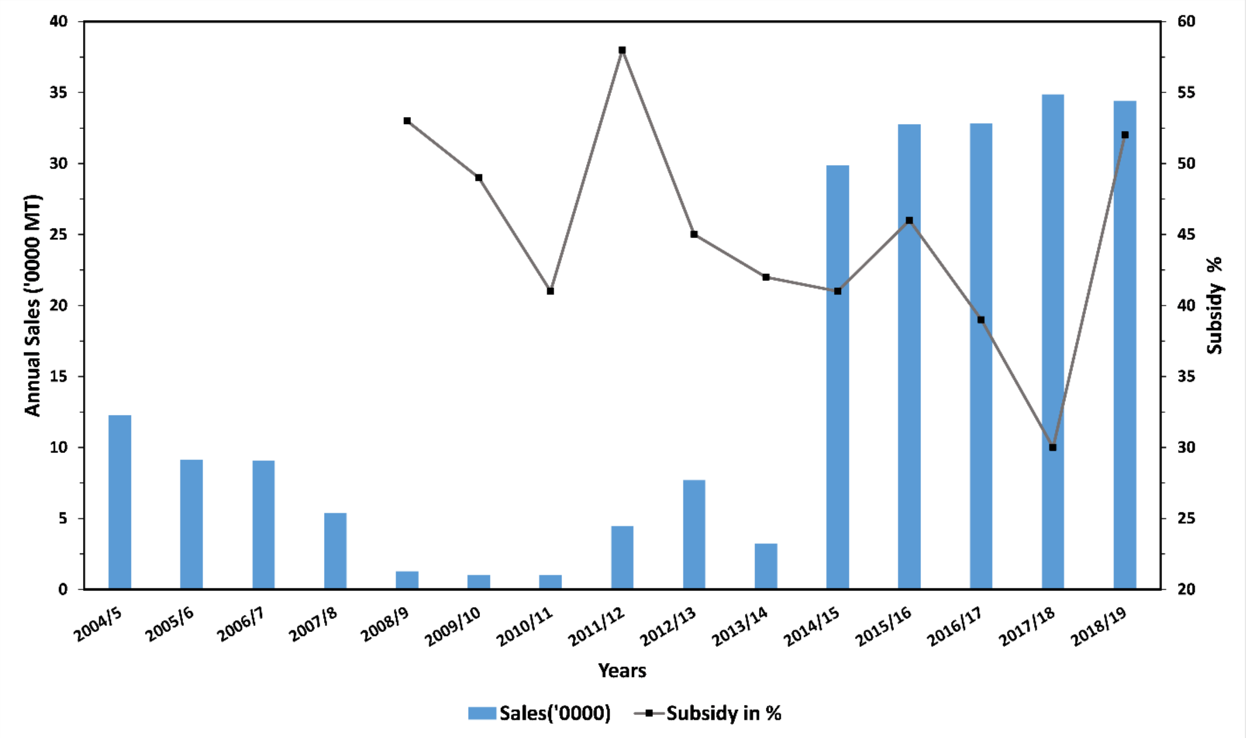

Figure 2 Annual sales and subsidy % on chemical fertilizers (MoALD, 2020; MoF, 2021a; OAG, 2021)

Vision 2035

In order to improve agricultural yield and ensure food security, the government of Nepal has put forward different strategic plans with the target years to achieve the goal. The Agriculture Development Strategy (ADS, 2015-2035), has been implemented to direct Nepal's overall agriculture sector for the next 20 years with a focus on food self-sufficiency by 2035 (Chemjong & KC, 2020; MoALD, 2014; MoF, 2020a). In the first five years, the strategy aimed to reduce the trade deficit in food grain from 16% to 0%, however, the deficits have further increased to 20% which highlights the wrong trajectory of the national plan (MoALD, 2014; MoF, 2020b). Similarly, Nepal has adopted SDGs of ending hunger, ensuring access to safe, nutritious and sufficient food, and ending all forms of malnutrition by doubling agricultural productivity by 2030

(Khadka & Bhandari, 2020). Yet, the average annual growth rate in agricultural production in the last decade was merely 3.2% which suggests the need for extra effort in the coming decade to achieve the goal (MoF, 2020a). Studies have shown agricultural production could be increased with an effective and adequate supply of chemical fertilizers. There are many instances in the world of increased agricultural productivity with sufficient fertilizer usage. In Punjab (India), the productivity of rice increased from 2733 kg/ha to 3506 kg/ha, wheat from 2730 kg/ha to 4563 kg/ha, and maize from 1602 kg/ha to 2793 kg/ha with the increase in fertilizer consumption from 181.8 kg/ha in 1980-81 to 308.9 kg/ha in 2000-2001 (Vatta *et al.*, 2013). The increase in agricultural productivity of Punjab boosted the overall economy, reduced poverty, and contributed to the self-sufficiency of food at the national level (Sidhu & Bhullar, 2006). Similarly, Mexico became self-sufficient in food by the 1970s when fertilizer consumption was increased from 2.8×10^3 MT in 1940 to 1067×10^3 MT in 1978/79 (Sonnenfeld, 1992). The increase in fertilizer usage in Mexico increased the production of wheat from 500×10^3 MT in 1940 to 5200×10^3 MT in 1985 (Sonnenfeld, 1992). Moreover, the agricultural revolution in Bangladesh, Vietnam, Japan, Taiwan, and the USA suggests the important role of fertilizer in increasing food productivity and developing self-sufficiency. Thus, urea manufacturing units in the country could ease the supply and use of fertilizer and help meet the goals of food security and self-sufficiency by 2035.

UREA MANUFACTURING TECHNOLOGIES

Urea manufacturing technologies mainly differ in their use of fuel type for the raw materials as shown in Figure 3. The raw materials for urea manufacture are CO_2 and NH_3. Ammonia in turn is made by reacting H_2 and N_2. The fuel type used to acquire CO_2 and H_2 is what differentiates the different processes as shown in the figure below. The underlying principles of all the processes are the same. The two main reactions involved are:

$$CO_2 + 2NH_3 \leftrightarrow NH_2COONH_4 \quad (1)$$

$$NH_2COONH_4 \leftrightarrow NH_2CONH_2 + H_2O \quad (2)$$

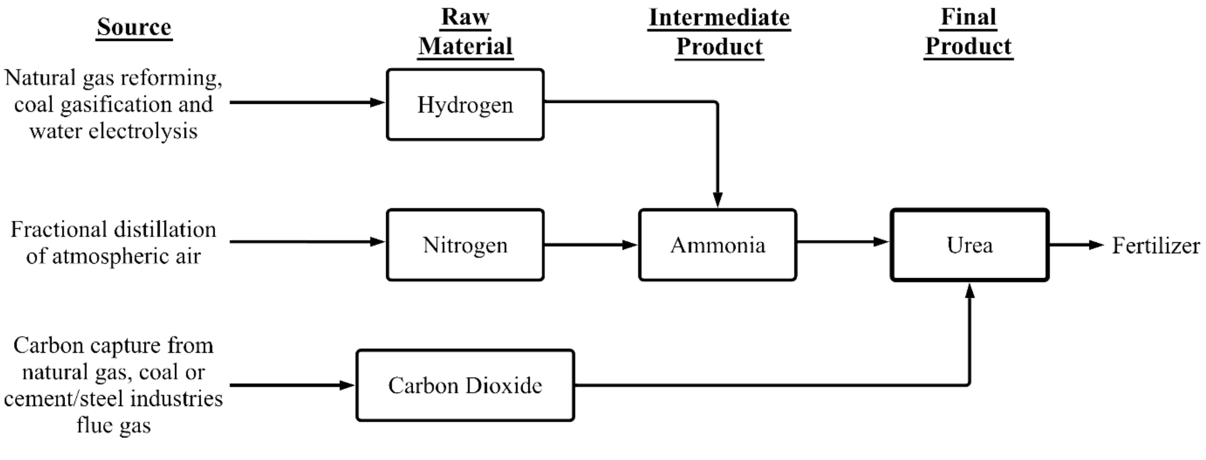

Figure 3 Block diagram of the urea production process

Urea Production

CO_2 and NH_3 are fed to the synthesis reactor at high temperature (180°C-210°C) and pressure (~150 bar) to form ammonium carbamate (NH_2COONH_4) which is then dehydrated to urea (NH_2CONH_2) (Rugone, 2016). The reaction is reversible and exothermic (Copplestone & Kirk, 1998). The urea so formed is a mixture of ammonia, ammonium carbamate, carbon dioxide, and urea where the unconverted carbamate is decomposed back to CO_2 and NH_3 by stripping with CO_2 (Copplestone & Kirk, 1998). Urea solution is then evaporated to make the solution concentrated and turned into granules using granulators.

Ammonia Production

Ammonia is manufactured by reacting nitrogen and hydrogen over a catalyst bed at high temperature and pressure. This is the conventional principle of ammonia production given by the Haber-Bosch process —the most commonly used method for ammonia production (Humphreys *et al.*, 2021; Yapicioglu & Dincer, 2019). Two other promising methods based on similar principles are solid-state synthesis and cryogenic air separation (Yapicioglu & Dincer, 2019). Typical industrial processes are carried out at temperatures between 300 to 500°C and pressures between 100 to 300 bar over several catalyst beds of Fe_3O_4 to increase the overall conversion (Giddey *et al.*, 2013). Based on production scale and conversion requirements, several catalysts such as derivatives of iron, cobalt, nickel, and ruthenium are being used or are under development. (Humphreys *et al.*, 2021).

CO_2 Capture

The CO_2 capture process is the same for natural gas, coal, or cement/steel industry flue gas. The steam reforming of natural gas and coal gasification process (described below) both produce a mixture of CO_2 and other gases (H_2, CO) which needs to be separated for use in a urea manufacturing plant. Likewise, CO_2 needs to be separated from the mixture of gases (flue gas) produced during cement or steel production. Although several capture technologies such as absorption, adsorption, cryogenic distillation, and membrane separation exist for CO_2 capture, the chemical solvent-based absorption technology is the most widely and commercially proven capture technology (Aschenbrenner & Styring, 2010; Lv *et al.*, 2012; Olajire, 2010). In this process, the gas stream is passed into an absorption chamber where it comes into contact with solvents such as monoethanolamine which absorb CO_2 from the gas. The CO_2-rich solvent is heated with steam in a second column (known as a stripping chamber) to recover CO_2 and the solvent is recycled again for absorption. The process is one of the most efficient processes with a CO_2 recovery rate of 98% and product purity of up to 99% based on the solvents used (Gupta *et al.*, 2003).

Hydrogen production

There are three major pathways for producing hydrogen: steam reforming of natural gas, coal gasification, and water electrolysis.

Steam Reforming of Natural Gas

In steam-methane reforming, high-temperature (700°C - 1000°C) steam reacts with methane in the presence of catalysts to form H_2, CO, and small amounts of CO_2 (Speight, 2020a, 2020b; Summa *et al.*, 2019). CO is further converted to CO_2 by a water gas shift reaction where CO reacts with steam to form CO_2 and H_2. CO and CO_2 are separated from the gas mixture to obtain high purity H_2. CO_2 is separated by chemical and physical scrubbing processes and the remaining CO and CO_2 are removed by the shift methanation process where CO and CO_2 react with steam to form methane. (Basile *et al.*, 2015). The steam-methane reforming process is 70-80% efficient and about 48% of global hydrogen production comes from this method (Luitel, 2014; Ursua *et al.*, 2012).

Coal Gasification

Hydrogen is produced from coal by reacting coal with oxygen and steam at high temperature and pressure. The process is called gasification which is the devolatilization of feedstock and breaking of weaker chemical bonds to yield tars, oils, phenols, and hydrocarbon gases (Stiegel & Ramezan, 2006). The gas mixture produced is called syngas which contains H_2, CO, and CO_2. The syngas composition is highly dependent on coal quality, O_2 and H_2O (steam) ratio, operating conditions, and the gasification technology adopted (Wagner *et al.*, 2008). The syngas is purified based on the purity requirements and then reacted with steam to get the CO in gas to produce additional H_2 and CO_2 (Stiegel & Ramezan, 2006). The CO_2 is then separated from H_2 using the sequestration process mentioned above.

Water Electrolysis

The electrolysis process is simply the dissociation of water into H_2 and O_2 with the help of an electric current. The promising electrolysis methods to date are alkaline, solid oxide, proton exchange membrane, and microbial electrolysis. All these electrolysis methods are carbon neutral and can be integrated with renewable energy sources such as hydropower. The alkaline electrolysis method is the commercially proven and most efficient process that is widely used for large-scale applications (Bhandari *et al.*, 2013; Kumar and Himabindu, 2019; Schmidt *et al.*, 2017; Ursua *et al.*, 2012). Alkaline water electrolysis uses 25%-30% potassium hydroxide (KOH) solution as electrolyte and sodium hydroxide (NaOH) and sodium chloride (NaCl) as catalyst (Keçebaş *et al.*, 2019). The purity of hydrogen produced ranges from 99.7% to 99.9% and process efficiency is more than 80% (Kotowicz *et al.*, 2016). Moreover, the alkaline electrolysis process also produces chlorine gas (Cl_2) which is widely used in the water treatment process.

COMPARISON OF THE MANUFACTURING PROCESSES

Availability of Raw Materials

Natural gas

The occurrence of natural gas has been recorded in different places in Nepal with estimated deposits of 316 million m^3 of methane gas with a calorific value of 7200 kcal/m^3 (Luitel, 2014; OIBN, 2017). The deposits have been discovered in the Kathmandu valley's key areas, including Dailekh and Mustang. Natural gas deposits in Kathmandu Valley have up to 40% water (Paudel, 2019). A feasibility study in 1996 recommended the commercialization of natural gas in the form of LPG by extraction of gas from the Tripureshwor reserve (47 million m^3 of gas in a 4 km^2 area (Luitel, 2014)) but ended up without implementation (Paudel, 2019). Thus, Nepal must import natural gas from India, China, or Bangladesh for establishing a urea plant in the country.

Research undertaken by the Daayitwa organization in partnership with the Investment Board Nepal stated that a natural gas pipeline can be linked to the projected Indian pipeline of Barauni-Guwahati that runs close to eastern Nepal (Luitel, 2014). Another study by iDeCK mentioned the Jagdishpur, India pipeline to be viable if the urea plant is established at Dhalkebar, Nepal (OIBN, 2015). It needs a pipeline of around 200 km— a two-point distance in Google Maps, which needs an extra investment of around 108.78 million USD and a timeframe of 6 years to complete—referenced from the recently constructed Amlekhgunj-Motihari petroleum pipeline (Yadav, 2020).

Further progress on construction and investment to make this pipeline has not been traced till today.

The dependence on the import of the key raw material for a strategic national industry is a major concern. Moreover, the long-term uninterrupted supply at a fixed price from India is uncertain. The gas reserves in India are anticipated to be drained by 2040 and prices are projected to double by 2040 (Kumar *et al.*, 2020). Along with India, Nepal's possible neighbors to supply natural gas, China (geographically challenging) and Bangladesh have also been facing natural gas shortages and have been importing natural gas to balance their demand (Ahmed, 2011; Alam *et al.*, 2019; Li *et al.*, 2020). In response, India has already started the switch from natural gas to coal-based urea plants with its first coal gas-based urea plant estimated to be operational in 2022 (Kumar *et al.*, 2020). Similarly, a study on the volatility of urea production in Bangladesh found the natural gas shortage to be the problem for urea industries and suggested the switch to an electricity-based plant (Ahmed, 2011).

Coal

Coal deposits have been discovered in Nepal's Dang, Salyan, Palpa, and Rolpa districts grouped into four stratigraphic units: Gondwana Coal, Tertiary Coal, Quaternary lignite, and Eocene Coal (OIBN, 2017; Paudel, 2019; Sah & Paudyal, 2019). According to the US Energy Information Administration, Nepal has a total coal reserve of around 1100×10^3 MT (EIA, 2019). The coal is believed to be of low quality with high moisture content and a carbon content of around 15% (Luitel, 2014). According to the coal consumption statistics in 2018, Nepal produces about 28×10^3 MT of coal annually which is less than half of the per day demand for urea plants (EIA, 2019; OIBN, 2015). Thus, Nepal must import coal from China, India, or Bangladesh for establishing a urea plant in the country. Similar to natural gas, dependence on import of key raw material is of concern for national strategic industry. Moreover, depending upon price volatility, long-term uninterrupted supply at a fixed price from India is uncertain.

Electricity

The hydropower potential of Nepal is about 83000 megawatts (MW) which can be commercially exploited for up to 42000 MW (Zhou *et al.*, 2020). The present installed capacity of hydropower electricity is 1182 MW as of 2019, another 3150 MW of Hydropower projects are under construction and an additional 20000 MW of hydropower projects are under consideration (Mali *et al.*, 2021; Thapa *et al.*, 2021). Nepal is expected to generate a total of 12000 MW of electricity by 2030 of which 3000 MW is expected to be in surplus (Thapa *et al.*, 2021; Thapa & Thapa, 2020). In addition to hydropower, solar, wind energy, and biomass have seen major developments with an installed solar capacity of 54 MW in 2019 where 50 MW developed in the last ten years (IRENA, 2020). Moreover, Nepal can fulfil all of its energy demands with solar photovoltaics by covering just 1% of its land surface with panels, effectively eliminating the need for fossil fuels (Lohani & Blakers, 2021). At present, Nepal has surplus electricity in the wet season with a shortfall in power in the dry season as the majority of the existing hydropower plants are run-of-river types (Thapa *et al.*, 2021). The consumption and output imbalance has been maintained with the cross-border trading of electricity between India and Nepal.

Nepal has already begun researching and studying a green hydrogen-based economy, which would inevitably impact the hydrogen supply for a chemical fertilizer plant. A Memorandum of Understanding (MOU) has been signed between Nepal Oil Corporation (NOC) and the Green Hydrogen Lab at Kathmandu University to begin the development, transmission, and production of green hydrogen from surplus hydroelectricity. A maximum of 336.38×10^3 tons of hydrogen can be produced annually with a forecast rise in surplus energy from 2102 GWh in 2022 to 16820 GWh in 2028 (Thapa *et al.*, 2021). The cost of generating hydrogen is expected to be in the range of USD 1.17 - 2.55 per kg, making it cost-competitive with hydrogen derived from natural gas and coal (Thapa *et al.*, 2021). Based on the renewable energy potential of Nepal and the energy projects in the developmental stage, hydrogen production through electrolysis appears to be the prudent, effective, economic, and strategically viable pathway for establishing a urea plant.

Cement industries flue gas

Cement industries are one of the fastest-growing industries in Nepal due to the proven limestone deposits of 420 million MT (Singh & Shakya, 2016). As of 2019, there are altogether 59 installed cement industries in Nepal with a production capacity of about 6 million MT annually (Sah *et al.*, 2019). Consequently, cement industries are one of the major sources of carbon emissions. Capturing CO_2 from cement industry flue gas emissions can provide feedstock for fertilizer plants and reduce our CO_2 emissions. Studies in the past have already mentioned flue gas to be the possible source of feedstock for establishing a fertilizer plant (JICA, 1984; Luitel, 2014; OIBN, 2015). The annual CO_2 emissions from the cement industry of Nepal in the year 2014 was estimated to be 365.4×10^3 MT and is expected to increase to 2292.9×10^3 MT in the year 2030 under normal production growth (Singh & Shakya, 2016). The stoichiometric calculation (reactions 1 and 2) with 60% CO_2 conversion efficiency suggests the need for 977.7×10^3 MT of CO_2 annually for the production of 800×10^3 MT of urea. Based on the stoichiometric calculations and the cement industry CO_2 emissions data, we have more CO_2 feedstock than required for establishing a urea plant in the country. Moreover, the CO_2 capture process is the same as the CO_2 capture process needed in the natural gas or coal-based manufacturing processes and can be easily retrofitted in the existing cement plants.

Environmental Impact

While ammonia to urea production is common for all processes, the preceding feedstock extraction or production process determines the environmental impact of a pathway. So, the following section analyzes the natural gas, coal gasification, and electrolysis pathways for urea production based on their environmental impacts.

Raw material extraction/mining/supply

Although the coal deposits and the quality of coal in Nepal are not adequate for sustaining a urea industry, there are several environmental challenges associated with coal mining if the country decides to open new coal mines. Land subsidence, air and water pollution, and displacement of wildlife are some of the environmental issues associated with coal mining (Bian *et al.*, 2010). Land subsidence reduces crop production, plant death, surface fracture and soil loss, drainage system failure, and structural damage in buildings (Bian *et al.*, 2010). Coal mines discharge huge amounts of mine water, which lowers the pH and increases the level of total suspended solids, total dissolved solids, and some heavy metals (Tiwary, 2001). Drilling, blasting, and movement of vehicles and machinery emit particulate matter and gases including methane, sulfur dioxide, and oxides of nitrogen, causing air pollution (Bian *et al.*, 2010). Hydraulic fracturing of shales, the most common technique used in natural gas extraction, results in similar environmental problems. Drilling, blasting, and installation of pads result in noise pollution and land disturbance of the site, affecting crops, animals, and human settlement (Walton & Woocay, 2013). It also creates fast permeability pathways, because of which hydrocarbons and other fluids contaminate aquifers near the site (Reagan *et al.*, 2015). Fugitive releases of methane, ethane, and other volatile organic compounds (VOC) like benzene and toluene from leaks and pressure-relief venting valves, flowback water, and other production activities can increase problems with ozone (Walton & Woocay, 2013). Likewise, the extraction of natural gas deposits in Kathmandu is filled with challenges due to the large settlement around the site. Further, domestic natural gas deposits are not adequate for the urea industry and need to be imported via distribution pipeline which will create additional ecological challenges such as destruction of forests, displacement of wildlife, and water, soil, and air pollution due to potential leakages. Moreover, both coal and natural gas mines are prone to increased workplace accidents (Bian *et al.*, 2010; Walton & Woocay, 2013).

Unlike coal and natural gas mines, hydropower plants are established beside a river without altering land structures as extensively as natural gas and coal mines. The reservoir-based hydropower energy, however, will modify habitats of aquatic life, inhibit the migration of fish, and modify hydrological regimes (Faizal *et al.*, 2017; Yüksel, 2010). Dead trees (trees with a part of it above the water in the reservoir) and anaerobic soft underwater vegetation decay will emit carbon dioxide, and methane respectively (Fearnside, 2005). A flood during the construction of a dam can also temporarily introduce methyl mercury to the food chain (Calder *et al.*, 2016). Although all energy extraction processes will negatively affect the environment, hydropower energy has a comparatively minimal environmental impact.

Process Emissions

In terms of urea production, both the natural gas and coal-based processes are low emission processes as the CO_2 formed by burning the fuel (methane and carbon) is captured and utilized as the feed source for urea. Likewise, the electrolysis of water with electricity from a renewable source like hydropower is a carbon-neutral process to produce hydrogen. The CO_2 capture from cement flue gas, on the other hand, is a carbon-negative process. Cement industries are the largest emitter of CO_2 in Nepal which makes the capture process desirable in line with the country's commitment to be an emission-free country. To this end, Nepal has pledged to commit $3.4 billion to mitigate GHGs in its Nationally Determined Contributions (NDC) document submitted to United Nations Framework Convention on Climate Change (UNFCCC) as per the Paris Climate agreement (MoFE, 2020). Thus, a hydropower-powered electrolysis and CO_2 capture-based urea manufacturing plant appears to be in line with the country's commitment to sustainable economic development.

Sustainability

Raw material for electrolysis is renewable, while natural gas and coal are rapidly exhausting from the planet. At the current capacity of all of the proven reserves and 2018's consumption level, natural gas in the world will exhaust in about 52 years (EIA, 2018). Natural gas reserves of Nepal would exhaust in about 1500 days to operate a typical natural gas-based urea plant, which consumes 5.5 Gcal of natural gas per MT of urea fertilizer produced (Luitel, 2014). Similarly, the world coal reserve excluding unproven reserves will exhaust in about 133.5 years at 2019's level of consumption (EIA, 2019). The coal reserve in Nepal, however, will exhaust in 1.5 years at 2019's rate of consumption (EIA, 2019). Further, the period will be shortened if coal is used in hydrogen production for the urea plant (EIA, 2019). In comparison to natural gas and coal, hydropower energy (42000 MW capacity) is abundant in Nepal for long-term sustainable development.

Cost

Table 2 summarizes the cost of establishing a urea plant using different manufacturing processes based on the detailed project report by iDeck under the Investment Board of Nepal (OIBN, 2015). As seen from the table, the natural gas-based manufacturing process is cheaper than either coal-based or electrolysis-based process. The iDeck report did not provide a clear breakdown of the electrolysis-based ammonia production process which could explain the unusually high cost of the ammonia production process. Similarly, there are no good precedents in the world for a cost comparison of the electrolysis-based ammonia manufacturing process.

Although the natural gas-based process appears to be cheaper, the operating cost per year for manufacturing urea could be higher for the natural gas-based process compared to the electrolysis-based process in the long run due to the cross-country import of natural gas. In addition, the natural gas-based process would require further investment and time to construct a natural gas pipeline from India. The electrolysis-based urea plant, on the other hand, would utilize the excess hydropower energy expected to be produced in the country. A detailed economic study specifically focused on electrolysis and CO_2 capture -based urea technology should be conducted by the government to get a clearer picture of ways to move forward. In this regard, the baseline value for capturing CO_2 from cement flue gas was recently estimated by Devkota et. al (Devkota *et al.*, 2021). The study estimated the cost of carbon capture to be $86/ton and the price of capture was shown to be highly dependent on the cost of electricity which presents a huge opportunity for Nepal (Devkota *et al.*, 2021). We would like to make a note that baseline values for electrolysis-based hydrogen production system are areas of the current study and will be published accordingly.

Table 2 Cost comparison for establishing a urea plant in Nepal (OIBN, 2015)

S.N.	Item	Electrolysis (Million USD)	Coal (Million USD)	Natural Gas (Million USD)
1	Ammonia Plant	767	387	193
2	Urea Plant	109	104	109
	Sub Total for Main Plants	876	491	302
3	Off- Site Facilities	143	202	143
	Sub Total for Main Plants and Off –Site Facilities	1019	693	445
4	Project Preparatory Expenses (Spare, Engineering, PMC)	100	113	100
5	Land and Land Development, Township, Non-Plant Buildings	43	48	43
6	Margin and Working Capital	8	8	8
7	Contingency	59	42	30
8	Net Commissioning Expenses	4	4	4
	Total Cost before IDC	1232	903	628
9	Interest During Construction	73	50	37
	Total Project Cost	**1,305**	**953**	**665**

OPPORTUNITY FOR ECONOMIC AND TECHNOLOGICAL DEVELOPMENT

The urea manufacturing plant could solve the perennial fertilizer shortage problem of Nepal and significantly help to increase agricultural productivity and to reduce the dependence on food imports. This would fulfil the SDG's goal of food security. In addition, the urea plant could be a catalyst for economic and technological development in Nepal. The massive urea plants, irrespective of the processes chosen, will mobilize an entire generation of national manpower from the governmental, educational, and private sectors which will energize the economic and technological development of the country. Although an established process, the continuous and long-term running of the national interest industry will require academic and industrial cooperation which will have synergistic effects on the individual sector development. New industries foster new research in academic institutions that could range from solving operational problems to developing new and more efficient processes. The research in turn will help the industries run continuously and sustainably. Big projects such as this will also help develop supporting industries and manpower that impact the overall economy of the country. Of the three technologies described, the electrolysis-based manufacturing process seems to be the most challenging as it is a fairly new and ever-improving technology. Based on the raw material availability (especially hydropower electricity) and the benefits of capturing CO_2 from the atmosphere, this technology presents an opportunity for the country to research and develop an edge on the electrolysis and CO_2 capture based urea technology.

CONCLUSIONS

Agriculture is the major source of income for a majority of the people in the LDCs, therefore, agricultural development will directly help to fulfil the SDGs of 'no poverty'; 'zero hunger'; 'good health and well-being'; and 'decent work and economic growth'. Nepal, an LDC, has two-thirds of the population involved in agriculture, yet, food production is very low and the country is highly dependent on food import. The low agricultural productivity can be attributed to inadequate fertilizer use as the country depends on fertilizer import. To meet the fertilizer demand, increase productivity, drive an agro-based economy and thus meet the SDGs, Nepal could benefit from establishing a urea manufacturing plant. Urea production uses CO_2 and NH_3 as raw materials, where NH_3 is produced by reacting H_2 and N_2. Based on the processes used to acquire H_2 and CO_2, there are three major pathways to produce urea: steam reforming of natural gas, coal gasification, and electrolysis of water. In terms of raw material availability and sustainability, urea manufacturing based on hydropower-powered electrolysis and CO_2 capture from cement industries exhaust appears to be the better route for sustainable development. The urea plant based on natural gas or coal will increase foreign dependence on the raw material for a national strategic industry vital to achieving SDGs. The COVID-19 restrictions have underscored the necessity of self-reliance and the electrolysis-based pathway has a reliable raw material supply. Moreover, the electrolysis pathway coupled with CO_2 capture also contributes to the national interest of Nepal to be an emission-free country. A domestic urea plant will ensure economic and technological development, higher agricultural productivity, and increased food security. A more detailed study on the economics of electrolysis-based urea manufacturing for sustainable economic development is recommended to foster a national plan for Nepal.

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AUTHOR CONTRIBUTIONS

First two authors contributed equally.

CONFLICT OF INTERESTS

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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