



# Recent Progress in Refuse Derived Fuel (RDF) Co-processing in Cement Production: Direct Firing in Kiln/Calciner vs Process Integration of RDF Gasification

Prateek Sharma<sup>1,2</sup> · Pratik N. Sheth<sup>2</sup> · B. N. Mohapatra<sup>1</sup>

Received: 15 October 2021 / Accepted: 28 May 2022 / Published online: 23 June 2022  
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

## Abstract

Refuse-derived fuel (RDF) from municipal solid waste (MSW) is an alternative fuel (AF) partially replacing coal/petcoke in a calciner/kiln of cement plant. The maximum thermal substitution rate (TSR) achieved through RDF is 80–100% in the calciner, while it is limited to 50–60% in the kiln burner. Different AF pre-combustion technologies, advancements in multi-channel burners, and new satellite burners have supported high TSR. Extensive efforts in modelling kiln burner and calciner lead to enhance TSR. However, the cement industry faces operational issues such as incomplete combustion, increased specific heat consumption, reduced flame temperature, and kiln coating buildup. There is an interest in RDF gasification, a promising alternative to eliminate the operational issues of the cement industry, which needs to be integrated with the existing cement plant. The article reviews the integration of gasification in cement production and various experimental and modelling studies of the direct firing of AF/RDF in the kiln/calciner. The features and technology status of both approaches are compared. The different gasification integration technologies with varied configurations for cement plant calciner are highlighted. The article emphasizes the need to develop suitable calciner/kiln-gasifier models for predicting calciner output based on different RDFs.

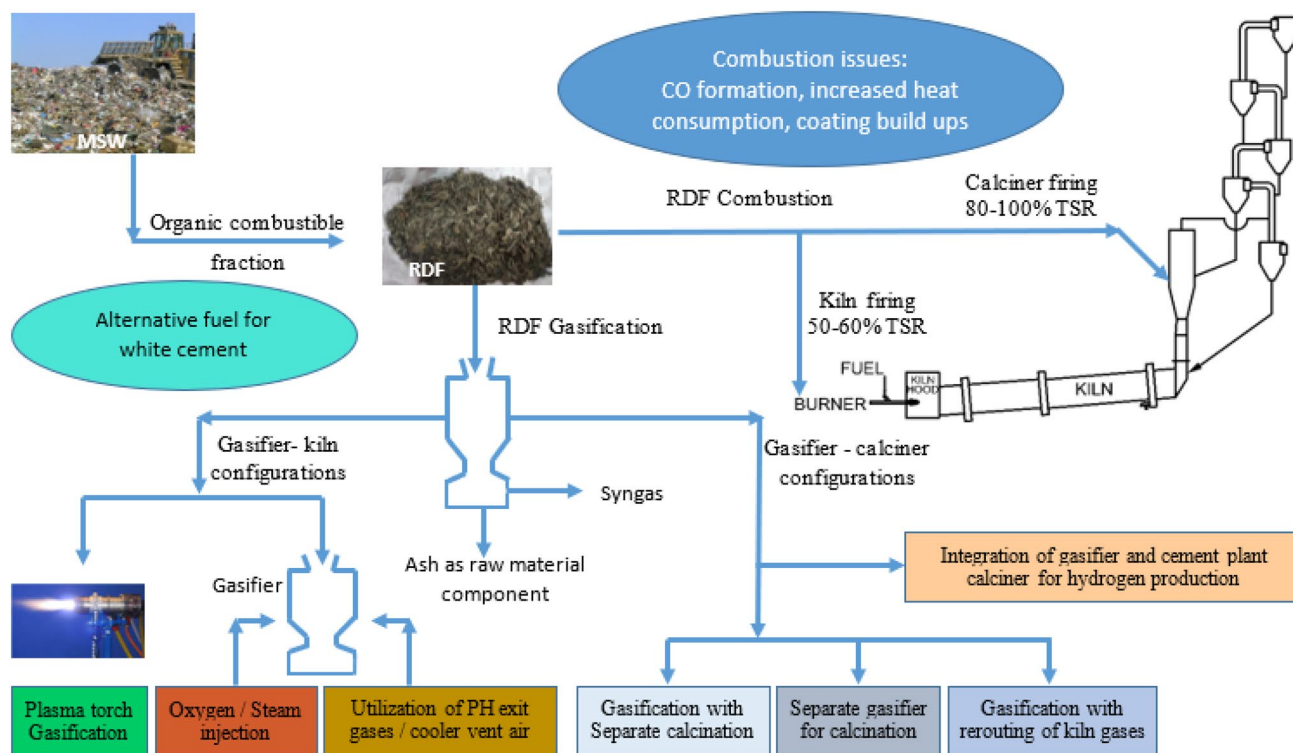
---

✉ Pratik N. Sheth  
pratik@pilani.bits-pilani.ac.in

<sup>1</sup> Centre for Mining, Engineering, Environment and Plant Operation, National Council for Cement and Building Materials, Ballabgarh, Haryana 121004, India

<sup>2</sup> Chemical Engineering Department, Birla Institute of Technology and Science—Pilani, Pilani Campus, Pilani, Rajasthan 333031, India

## Graphical Abstract



**Keywords** Refuse derived fuel · Cement production · RDF Gasification · Process integration · Calciner · Kiln

### Abbreviations

AF	Alternative fuel
MSW	Municipal solid waste
PTG	Plasma torch gasification
RDF	Refuse derived fuel
TSR	Thermal substitution rate

### Statement of Novelty

RDF is a heterogeneous alternative fuel that impacts kiln operation during direct combustion in cement plants. The article provides a holistic view of the current RDF utilization status in the cement industry worldwide, covering waste types, inventory, and TSR status in India and the world. The challenges of directly RDF utilization, calciner/kiln burner models, experimental studies, up-gradation in the calciner, modern pre-combustion technologies, satellite burners, and multi-channel burner types are discussed. The significance of this article lies in the extensive review of calciner/kiln modelling vis a vis gasifier models and different kiln/calciner-gasifier integration configurations. This review can support future research in developing suitable

calciner-gasifier models for predicting calciner output based on varying RDF input to gasifier without experimental trial runs.

### Introduction

Cement is one of the key essentials in the construction sector and forms the backbone of a nation's economy. The total world cement production is around 4.1 billion tonnes in 2019, with India being the second-largest cement producer after China [1, 2]. The current annual production of the Indian cement industry is 334.48 million tonnes as of March 2020 [3, 4]. India's UltraTech Cement Ltd. stood at 6th position amongst the top ten cement companies globally, with an installed cement production capacity of 90 million tonnes annually [5]. According to the technology roadmap by the international energy agency [6], global cement production is poised to grow by 12–23% from 2014 to 2050. The cement industry is an energy-intensive process that requires 3.3 GJ/tonne of clinker [7] with a significant share of heat requirement from the combustion of fossil fuels. Waste utilization as an alternative fuel for co-processing in the cement industry has gained popularity due to its key

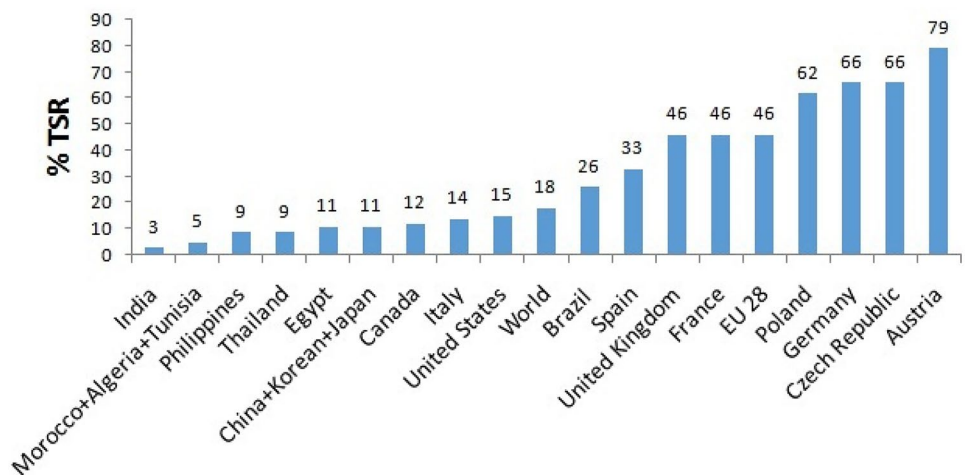
advantage of complete waste destruction in a rotary kiln at 1400–1450 °C without impacting clinker quality [8]. The alternative fuel (AF) utilization in the cement industry is measured in terms of the thermal substitution rate (TSR), the rate of substitution of fossil fuels by alternative fuels in terms of thermal energy.

### Status of Waste Utilization for Co-processing as an Alternative Fuel in the Cement Industry

The TSR for alternative fuels utilization in the Indian cement industry in 2017 was around 3% (currently 5%), which is very low compared to the European nations of approximately 46% and the world average of 18%, as shown in

Fig. 1 [9]. The share of biomass and waste in the Indian cement industry is anticipated to increase to 10% by 2030. It is expected that the share of fossil fuels utilization in global cement production shall reduce from 94% (2014 as baseline year) to 67–70% in 2050. This will lead to a reduction in direct CO<sub>2</sub> intensity to the tune of 32–38% [6]. The cement companies in India, Ambuja Cements Limited and ACC Limited, had TSR of 5.36% [10] and 4.47% [11] respectively in 2019. Ultratech Cement Limited and Shree Cement Limited stood at 3.1% TSR (FY 2020–21) [12] and 1.2% TSR (FY 2019–20) respectively [13]. Dalmia Cement Limited stands out at 8% TSR for FY 2020–21 with a significant share from RDF [14]. Few cement plants have achieved TSR in the range of 20–25% [15]. The type of waste utilized as an alternative fuel along with the source of generating industry and quantity is given in Table 1.

**Fig. 1** Status of % TSR of the cement industry for different nations



**Table 1** Type of waste utilized as AF in the Indian cement industry [8, 16–18]

Source industry	Type of wastes generated	Generation quantity (million tonnes per annum)
Urban local bodies	Refuse derived fuel derived from Municipal solid waste (MSW)	10.47 [19]
Automobile	ETP Sludge, paint sludge, oily rags	7.17 [20]
Paints and related	Paint sludge, chemical sludge, process waste	
Petroleum	Oil sludge spent catalyst	
Pharmaceutical	Expired medicines, Process/distillation residue, organic spent solvent, spent carbon	
Beverage	Spent Carbon, Effluent treatment plant (ETP) Sludge	
Textile	ETP Sludge	
Paper, Plastics	Plastic waste	3.47 [21]
Tyres	Tyre derived fuel (TDF), Carbon black	0.60 [22, 23]
Agricultural	*Biomass (Rice husk, cotton stalk, etc.)	230 [24]
Woods and related	Wood chips	
FMCG, footwear	Expired products, plastics	3.30 (E) [25, 26]

E Estimated

\*Surplus

The Indian cement industry is gearing up fast to increase the uptake of waste for co-processing. Confederation of Indian Industry (CII) prepared a vision document that envisaged the TSR of 25% (15% from RDF only) by the year 2025, considering different types of waste and their availability [27].

### MSW Based RDF as an Alternative Fuel with Problems/Challenges in Utilization

Municipal solid waste (MSW) management is one of the challenging problems for countries all around the globe. The global generation of municipal solid waste is more than 2.1 billion tonnes annually, out of which 16% is recycled, and 46% is disposed of unsustainably [28]. It is expected to increase to 3.4 billion tonnes by 2050. China contributes a 15% share in MSW generation, which is the highest. The USA accounts for only 4% of the global population but has a high percentage of MSW, as given in Fig. 2 [28]. It is to be noted that the top ten cement-producing nations are also top solid waste-producing countries; thereby, the tremendous potential lies in the cement sector of these nations to utilize this waste [29]. It is anticipated that MSW co-processing in cement kilns in China can replace 75% of landfills and have substantial environmental benefits [30].

In India, MSW generation is around 62–65 million tonnes and is estimated to be 130 million tonnes by 2031 [19, 31].

The RDF obtained from MSW is generally 15–20% which is the combustible fraction of MSW excluding compostable and inert fractions. A Finnish company has developed a processing system that can convert 80% of MSW to RDF for a cement plant in the UAE [32]. As per the current scenario, the availability of RDF, considering the proximity of cement plants in India, is estimated to be around 13,600 tonnes of RDF per day, equivalent to 4.96 million tonnes per annum [19]. A guideline has been developed by the ministry of housing and urban affairs (MoHUA) where Indian RDF grading has been done based upon the quality of RDF [19].

RDF utilization as an alternative fuel has its challenges. Abbas and Akritopoulos [33] reported that some cement plants in Europe achieved a TSR of 80–100% through RDF in the calciner. However, there are some operational challenges like hot spots and high CO emissions which need further optimization. The plants in European nations have well-established pre-processing and co-processing facilities and kiln bypass systems that facilitate high TSR in their plants. China, has 8% TSR with co-processing in more than 100 cement plants. It co-process 3.5 million tonnes per annum of municipal solid waste annually, having 10–15% plastic and 2 million tonnes of RDF containing 30–40% plastic [34]. In India, out of 148 integrated cement plants, only 59 plants are co-processing waste, mainly in the calciner [35, 36]. It has been reported that 0.6% contribution is due to RDF from the overall 4% TSR. Only a few cement plants achieved a TSR of more than 15% [15]. Two Indian cement plants have

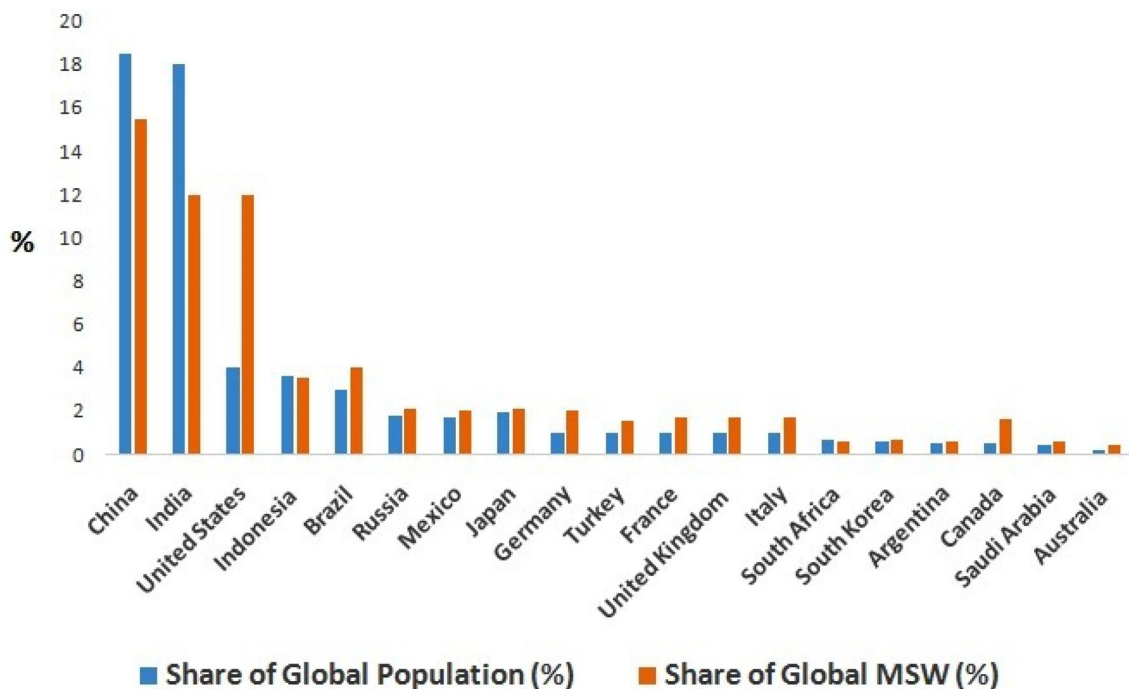


Fig. 2 Status of global municipal solid waste generation [28]

recently installed a kiln bypass and they are operating at 30% TSR using RDF as the main alternative fuel in the calciner. Therefore, to reach the value of 25% TSR on a sustainable basis round the year, more plants have to opt for kin bypass. Creating an enabling infrastructure for collection, segregation, and transportation of alternative fuels is also required. Cement plants that have achieved 15–20% TSR and aiming to increase it needs to invest in pre-processing and co-processing systems to maximize utilization in the calciner and kiln. The poor quality of waste, improper segregation, low calorific value, high chloride content, cost fluctuations, poor characterization facilities, system design flaws, operational issues, etc., are some of the challenges faced by the Indian cement industry during RDF utilization. Table 2 presents issues and benefits related to the RDF combustion under different categories of process, environment, and system design associated with negative or positive impacts. A negative impact in the process means an increase in specific heat consumption or reduction in clinker production due to AF utilization and vice versa. An increase in emissions indicates a negative impact on the environment during AF usage. Deteriorating clinker quality is also the negative impact of AF usage. Issues related to chute jamming are covered in system design aspects.

Sharma et al. [37] and Kukreja et al. [38, 39] highlighted several issues related to pre-processing and co-processing faced by the cement plants in India during RDF utilization. The lower heat value of 1800 kcal/kg with 25% moisture and odour are some of the major challenges observed by Dalmia Cement Ltd.-Dalmiapuram during RDF utilization, as reported by Rajamohan et al. [40]. One of the most common issues highlighted is the high chloride content in RDF, leading to operational challenges. Hence, it is the need of the hour that the cement industry particularly in India looks for some other options of thermochemical treatment to process the waste to overcome the above-mentioned challenges. Pyrolysis and gasification are two other thermochemical treatment technologies that can help reduce waste and a drastic saving of land from landfills. The main product of pyrolysis is the pyrolytic oil, and the yield is typically around 50–60% at optimum operating conditions. The pyrolysis process also releases gases which remain untapped and leads to pollution. It is envisaged that due to the pollution issues, the commercial process may not get the approval of the pollution board, or the costing may go high to curb the pollution. Moreover, pyrolytic oil utilization requires storage and a liquid firing system, which may cost the user. Several authors carried out the waste characterization using TGA, DTG, FTIR, and Py-GC/MS [41–44]. Bogusław et al. [45] highlighted the high content of tar in gas products. Hence, the RDF pyrolysis process at the lab scale may be used to develop the kinetic models and find the product yields. However, the authors believe that the commercial process development would be challenging. In contrast, gasification

offers unique advantages as the only product is syngas and may be directly burned in the calciner/kiln without any gas cleaning. Thus, gasification may be considered a suitable waste treatment technology for converting the solid form of waste to clean gaseous fuel with the removal of impurities from the pyro-processing system. Syngas has better combustion properties in the calciner than even small size solid waste directly fed to the calciner. Thus, a hard-to-burn fuel can be made easily combustible. In addition to the above, high moisture, which is problematic to the kiln system, will participate in gasification reactions to a certain extent and increase the CV of syngas by contributing to H<sub>2</sub> production through water gas shift reaction. NCV variations of the input fuel mix (coal and syngas) are reduced substantially due to consistent syngas composition. Moreover, it offers better clinker quality due to no additional ash in the clinker. Several articles cover the RDF gasification application in an internal combustion engine, electricity generation, etc. An 8 tonnes per day solid recovered fuel (SRF) gasification plant was set up in Y City, Korea, to produce syngas which was utilized further to produce power (235 kWh during 12 days) [46]. Another RDF gasification pilot plant was installed in Brazil to process 700 tonnes per day of RDF and generate 16.9 tonnes per day of syngas with a heating value of 4.6 MJ/kg [47]. In India, one RDF gasification plant was set up in Pune to generate 10 MW of power, but the plant could not be operational due to technical reasons [48].

In view of the above, cement plants facing bottlenecks to enhance TSR above 15–20% shall be benefitted from gasification technology. Gasification integration with the cement industry shall help achieve the target of 25% TSR within the timeframe. The government of India has set a target of 100 million tonnes of coal gasification by the year 2030 with an investment of Rs 0.4 million crores [49, 50]. Once gasified coal usage is achieved in the cement industry, it will promote co-gasification of coal and waste, having the advantage of improved syngas quality. This article discusses the integration of gasification with cement production, an alternative to direct combustion technology. An extensive review of different configurations of kiln/calciner with gasifier, kiln/calciner direct combustion models, and pilot studies will pave the way to develop suitable models for calciner and gasifier as a single unit. There is no article covering the review of the integration of gasification with the cement industry as per the authors' knowledge.

## The Cement Manufacturing Process and the Gasification Process

An overview of the cement manufacturing process and gasification is reported in this section to ease the readers understanding of the integration concept and scope of both processes.

**Table 2** Summary of the problems/challenges of utilizing RDF directly as a fuel for the cement industry

Source	Significance of the article	Impact on system parameters						
		Process	Environment	System design	Clinker quality	Cement quality	Coating/buildup problem	Solution proposed
[51]	<ul style="list-style-type: none"> <li>Emphasized the change in the existing system</li> <li>Discussion on AF firing location</li> <li>Adverse effects on clinker quality</li> </ul>	Negative	–	–	Negative	Negative	Negative	No
[52]	<ul style="list-style-type: none"> <li>Highlighted the usage of chlorinated RDF in clinker production by capturing the excess chlorine into the clinker</li> <li>The addition of sulfated materials such as natural gypsum, synthetic gypsum, plasterboard, etc., added to the raw meal having a minimum sulfur quantity of 30% is studied for chlorine fixation in the clinker</li> </ul>	Negative	–	–	Negative	Negative	Negative	Yes
[53]	<ul style="list-style-type: none"> <li>A case study is presented on calciner optimization to achieve 100% TSR in the calciner of a German cement plant</li> <li>The CFD simulations were carried out to replace fine RDF with coarser one having a lower heat value</li> </ul>	Negative	Negative	Negative	–	–	Negative	Yes
[54]	<ul style="list-style-type: none"> <li>It covers the status of AF utilization in India, focusing on the RDF challenges, opportunities, and plant experiences</li> </ul>	Negative	Negative	Negative	Negative	Negative	Negative	Yes
[55]	<ul style="list-style-type: none"> <li>Different proportions of fuel mix (RDF and petcoke) for preparing the clinker &amp; cement</li> <li>Cement is tested for different mineralogical parameters &amp; relevant standards</li> <li>It was concluded that 15% of RDF in the fuel mix would not pose any problem with clinker quality and environmental emissions</li> </ul>	–	Positive	–	Positive	–	–	–
[56, 57]	<ul style="list-style-type: none"> <li>A case study of M/s Vikram Cements Works—A Unit of UltraTech Ltd is presented</li> <li>It reported the usage of different types of alternative fuels, including RDF</li> <li>TSR achieved was 9.28% in 2012–13</li> <li>Preparation of RDF from MSW was also discussed in detail</li> </ul>	–	Positive	–	Positive	Positive	–	–

**Table 2** (continued)

Source	Significance of the article	Impact on system parameters						
		Process	Environment	System design	Clinker quality	Cement quality	Coating/ buildup problem	Solution proposed
[58]	<ul style="list-style-type: none"> <li>Impact assessment of alternative fuel utilization conducted for a cement plant considering coal as primary fuel using Aspen Plus software</li> <li>It was concluded that 25%, 15%, and 5% TSR could be achieved from waste tyres, air-dried RDF, and Meat and Bone Meal (MBM)</li> </ul>	Positive	Positive	–	–	–	–	–
[59]	<ul style="list-style-type: none"> <li>Trial runs for co-processing of RDF at pilot scale in a cement plant in Turkey</li> <li>Impact assessment is done for 8%, 12, and 15% TSR through RDF</li> </ul>	–	Positive	–	Positive	Positive	–	–
[60]	<ul style="list-style-type: none"> <li>CFD study conducted for assessing the impact of coating layers in the kiln with RDF as AF</li> <li>Impact on RDF conversion and clinker properties assessed</li> </ul>	Negative	–	–	Negative	–	–	–
[61]	<ul style="list-style-type: none"> <li>Trials run for RDF &amp; rice husk mix up to 5% TSR at a cement plant</li> </ul>	–	Positive	–	Positive	Positive	–	–

– No reference available in the paper

## The Cement Manufacturing Process

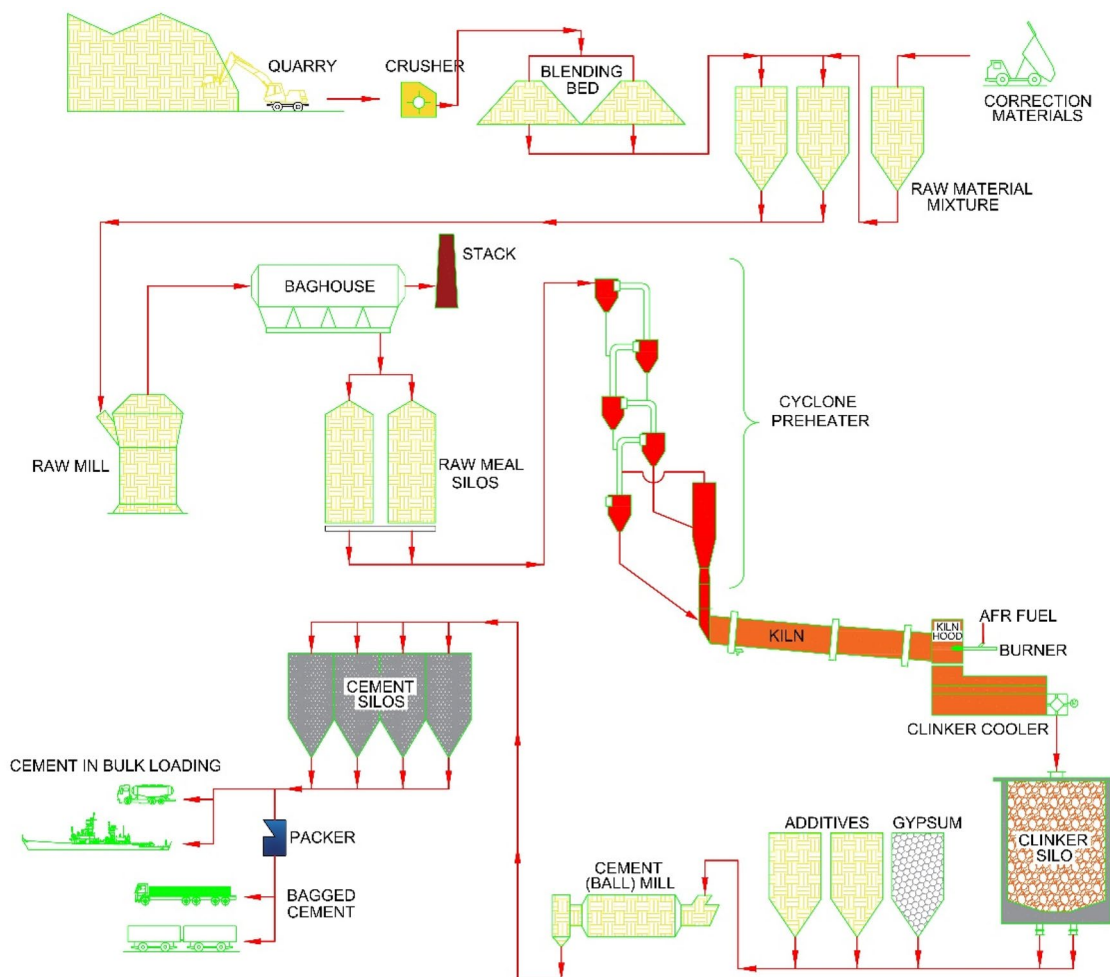
An outline of the cement manufacturing process is shown in Fig. 3.

Limestone, a calcareous compound, is the primary raw material for cement production. Argillaceous materials such as clay, sand, bauxite, laterite, etc., are used along with limestone to make a raw mix of suitable compositions. The limestone and clay are obtained from the mines in the first step. Limestone boulders are crushed in a crusher and further grounded to a fine powder. The ground raw meal is sent to the blending silo for homogenization of material. Homogenized material (kiln feed) is fed to preheater (5 or 6-stage cyclones). It is preheated, followed by reaches calciner and undergoes calcination. Carbonates present in kiln feed are calcined, and carbon dioxide is lost with preheater exhaust gas. Fine coal/pet coke and other alternate fuels are utilized as the fuel to meet the heat requirements for calcination. Calcined material enters the horizontally tilted rotary kiln at one end, and fuels such as coal/pet coke are fired through a burner pipe from the other end of the kiln. Calcined material is converted into the clinker at a temperature of around 1450 °C in the rotary kiln.

There are different reaction zones associated with a wide range of chemical reactions in the kiln system. Firstly, there is a drying zone where evaporation of free water takes place at < 100 °C. Then evaporation of the bound water occurs below 500 °C, and further temperature rise to more than 600 °C led to decomposition of carbonates present in kiln feed. It is a calcination reaction that continues above 900 °C. At 1200 °C and above, liquid formation takes place, followed by phase formation like  $C_2S$  ( $2CaO \cdot SiO_2$ ) and  $C_3S$  ( $3CaO \cdot SiO_2$ ) at > 1280 °C accompanied by evaporation of volatiles. The most critical zone is called the burning zone, where the clinker formation occurs [62]. Clinker from the kiln is then cooled to a temperature of 90–100 °C in a clinker cooler. Some portion of the air is recuperated back into the pyro-process system as secondary and tertiary air. The cooled clinker obtained from the clinker cooler is stored in a silo. Grinding it with gypsum produces ordinary Portland cement (OPC).

## Direct Firing of RDF

Solid fuels like coal and petcoke are finely grounded before firing in kiln and calciner to meet the heat requirement for



**Fig. 3** An outline of the cement manufacturing process

calcination and clinkerisation respectively. Any other solid alternative fuel like RDF with separate handling and firing system can replace these fuels. The direct firing aspects of RDF in kiln and calciner have been discussed in the next section.

### Direct Firing of AF/RDF in the Calciner

Limestone calcination is an endothermic reaction with heat of reaction of 178 kJ/mole [63]. This process is critical for clinker production as raw meal calcination affects the clinker quality, plant operation, and environmental emissions [64]. A calciner is a preferred option for AF firing since it requires a low temperature (800–900 °C) for calcination compared to clinkerisation (1400–1450 °C) in the kiln. It can handle low heat value fuels with varying characteristics. The utilization of waste as fuel, specific energy consumption reduction targets, and pollutant emission mitigation have led to calciner systems modification. Low NO<sub>x</sub> calciner [65], staged combustion [66], a pre-combustion chamber for alternative fuels

[67–69], calciner loop duct extension and controlled hot spot, etc., are some of the latest installations/modifications for calciner in cement plants. The norm for retention time in a calciner for new plants has changed from 3–4 s to 15–17 s so that the cement plants can fire large quantities of multiple solid/liquid fuels of varying characteristics with ease. The technologies such as calciner electrification [70], gasification, and carbon capture [71, 72] are not implemented yet and require extensive research including the modelling of the calciner. Several authors have tried to model calciner in the past and successfully validated calciner models and implemented them in cement plants. This section covers an extensive review of calciner modelling.

Calciner modelling has been divided into two categories: theoretical and empirical. Theoretical models cover Aspen Plus, CFD, material and energy-based models. Empirical includes data-driven, fuzzy logic-based models. Several works of literature are available on calciner models for different applications. Nhuchhen et al. [73] developed a thermal energy flow model from the energy and momentum balance



equations to achieve 50% TSR for twenty-four alternative fuels with natural gas as a primary fuel in the kiln. The model is difficult to implement due to time constraints, however, the devised regression equation can be helpful in future predictions while utilizing AF. Wydrych et al. [74] proposed a mathematical shrinking core model based on a combination of gas-phase and particle motion description. Further, this data is utilized for CFD model development to determine the pre-calciner's particle residence time and the radiative heat exchange between gas and limestone. Similarly, several CFD models are there where emissions are also predicted. Mikuleć et al. [75] studied the efficiency of the calciner along with pollutant emissions with the help of a CFD model. The model predicted the decomposition rate of limestone particles, burnout rate of coal particles, and pollutant emissions of a newly designed cement calciner. The major advantage is the demonstration of calciner characteristics that cannot be measured. Wang et al. [76] modelled the co-firing of high-carbon-ash (HCA) inside the cement calciner. A drop tube test was done, and the resulting fly ash was collected to study the unburnt carbon content. It is reported that 30% TSR is feasible. The study did not cover the fuel aerodynamic characteristics and different particle heat-up rates to particle size. Nakhaei et al. [77] studied the NO emissions from a cement calciner where two cases, case A petcoke fired and case B coal-fired, were simulated using CFD. The solid particles were simulated according to the Lagrangian formulation and the gas phase using the Eulerian approach. The extent of the calcination reaction, the emissions, and the temperature variations of the calciner were predicted and validated. The study shall be useful to develop futuristic NO emissions models for fuel mix with AF. Cristea et al. [78] developed a CFD-based 3D simulation model of a four-stage industrial calciner, and the results predicted are close to plant operational data. ASPEN models focused on predicting pollutant emissions and energy consumption at different TSRs for different alternative fuels. The model supports staged combustion simulation useful for controlling NO<sub>x</sub> emissions from the calciner by adjusting the input parameters. Machine learning and fuzzy logic models were data-driven where calciner input data (raw meal, fuel, tertiary air, etc.) were used to model and optimize the calciner output. Different approaches like statistical, mathematical with grey correlation analysis, just in time Gaussian mixture regression, hybrid clustering algorithm, DCS based were used extensively to model the calciner as specified in Table 3. All these data driven models are mainly for conventional fuels and not validated for alternative fuels.

### AF/RDF Firing in Kiln Burner

RDF firing in the main burner is more challenging as compared to calciner. Stringent alternative fuel quality like heat

value, particle size (2D and 3D), moisture content, etc., are crucial to firing in the main burner to avoid coating problems and impact clinker quality. Particularly, RDF size must be reduced to less than 25 mm for complete combustion in the kiln. At higher TSR, this size is further reduced to less than 3 mm [101]. Usage of different types of AF necessitates the modern multi-channel burners, which offer better flame shape control, high flame momentum, and the flexibility to use different kinds of AFs [102]. For burners, primary air pressure, flow rate, flame momentum, coal velocity, and solid alternative fuel velocity are vital varying parameters to optimize fuel combustion. The rising trend is to have a satellite burner in addition to the main burner, which can enhance RDF feeding by up to 50% [103]. High-temperature zone, and oxidizing conditions with sufficient residence time are some of the preconditions to achieving high TSR through a satellite burner. Xavier D'Hubert [104] compared kiln burners of reputed suppliers viz KHD Pyrojet, FCT Turbujet, Unitherm MAS, Polysius Polyflame, Dynamis D-Flame, FLSmidth Jetflex, Fives-Pillard Novaflam, ATEC-Greco Flexiflame, and Rockteq International for cement application. Richard Cunningham [105] presented a case study of Irish Cement Ltd (ICL), Limerick, Ireland, where the swirlax burner was modified to high thrust low primary air. Thus petcoke firing increases from 70 to 100% with increased sulphur intake from 4 to 4.5% without coating problems. Such solutions apply to all high sulphur alternative fuels. According to Lockwood et al. [106], RDF usage in kiln burner does not need any unique technology except an RDF handling system but limits the maximum utilization up to 30% considering environmental impact. One recent trial run has been conducted at Hanson cement's Ribblesdale plant in Lancashire. Fuel mix of hydrogen, meat and bone meal, and glycerine byproducts were cofired in kiln main burner, which showed promising results [107].

It is known that process measurements are difficult to carry out in a kiln; hence, it is always challenging to predict kiln inside conditions. Thus, kiln burner modelling has an essential role in determining fuel combustion behaviour concerning coating formation, emissions, etc. Several researchers have developed and validated kiln models as discussed further. Liedmann et al. [108] modelled the co-firing of RDF in kiln burner, focusing on RDF burnout behaviour and local heat release through CFD simulation. Out of the nine simulations performed, the base case showed a low RDF conversion rate of around 40%, with material falling onto the clinker bed. Separate lance introduction provided burnout improvement of 8% with enhanced residence time by over 30%. Haas and Weber [109] developed a kiln combustion model for cofiring RDF having HHV below 20 MJ/kg. The model examined the sintering zone temperatures with RDF properties to achieve process optimization. One of the CFD studies by Pieper et al. [60] assessed the impact of light and

**Table 3** Review of calciner/kiln burner models

Sr. No	References	Type of model	Parameters studied	Fuel	Input data	Specifications of the model	Key findings
1	[79]	Theoretical	CO <sub>2</sub> emissions and heat requirements	Coal	Fuel composition, Inlet temperature	CO <sub>2</sub> capture model, a thermodynamic model	Thermal fuel substitution was found to be more efficient than mass substitution. The conversions of CaCO <sub>3</sub> decreased with increased TSR
2	[73]	Theoretical	Emissions and Thermal energy intensity	24 different types of AF	LHV, Oxygen Fraction in fuel	A numerical model for various fuels	The thermal energy intensity increased with an increase in the fuel's moisture content, and a similar trend was found with O <sub>2</sub> content in the exit of the pre-calciner
3	[80]	Theoretical	Calcination at various temperatures	NF	Flow rates, reactor length, temperature	A numerical model to calculate the reaction rates and conversions	The rate of calcination increases and remains constant with the increase in temperature. And the calcination of CaCO <sub>3</sub> increased significantly with reduced particle size
4	[81]	Theoretical	Outlet temperature and emissions	Coal	Flowrate	Kinetic model coupled with CFD modelling	The flow characteristics and temperature in the calciner
5	[82]	Theoretical	Raw meal decomposition rate (RMDR)	Coal	Gas density, the heat of the pulverized combustion	Matlab Simulation	RMDR predicted within the acceptable limits for error
6	[58]	Theoretical (Aspen Plus)	Outlet temperature, NO <sub>x</sub> , O <sub>2</sub> , CO, CO <sub>2</sub>	Coal, Tyre Derived Fuel, Refuse Derived Fuel, Meat and Bone Meal	Raw material, Coal, Tertiary Air, Kiln Gas	Separate combustion and calcination models	RDF showed the least CO <sub>2</sub> emissions among the three fuels An increase in the thermal substitution of alternate fuels decreased the conversion
7	[83]	Theoretical (Aspen Plus)	Outlet temperature, NO <sub>x</sub> , O <sub>2</sub> , CO, CO <sub>2</sub>	RDF	Raw material, Coal, tertiary air, kiln gas	DD Calciner model with separate unit operations for fuel decomposition and combustion	Staging combustion could help control NO <sub>x</sub> emissions
8	[84]	Theoretical (CFD)	NO <sub>x</sub> and CO emissions, residence time, Burnout	Coal (Maun), Petcoke, and Oil	Inlet temperature, flow rates, tertiary air	Modelling the largest calciner in the world. It is an MI-CFD model	Increased usage of petcoke increased the NO <sub>x</sub> and CO emissions while increased oil consumption reduced them

Table 3 (continued)

Sr. No	References	Type of model	Parameters studied	Fuel	Input data	Specifications of the model	Key findings
9	[85]	Theoretical (CFD)	Temperature contour, velocity profile, calcination	Coal	Pulverized cement raw meal and coal flow rates, Air and flue gases flow rates, Coal Properties	The model has been prepared based on an IFRF Furnace	The turbulence caused by the swirling air increased the active length of the calciner. The role of the geometry of the calciner highlighted
10	[86]	Theoretical (CFD)	The hydrodynamic behaviour of a gas–solid flow in the precalciner	Coal	Continuity equations, Gas and solid-phase momentum conservation equations, Turbulent kinetic energy Equation of the solid phase	It is a numerical model that was later fed into the CFD Model	The velocity profiles showed that the bottom of the calciner had the highest turbulent flow field, and particles scatter more effectively
11	[74]	Theoretical (CFD)	NOx and CO <sub>2</sub> emissions	Coal	User-defined function, Reaction rate from the shrink core model	It is a shrink core model integrated into the CFD model	The particle residence time was calculated more accurately based on the shrink core model
12	[75]	Theoretical (CFD)	Emissions from the calciner outlet	Coal	Mass flow rates, Temperatures, Mass ratios	The model has a spiralling tertiary air inlet increasing the turbulence	The swirled flow enhanced the mixing phenomena, and lower CO levels were observed
13	[87]	Theoretical (CFD)	NOx emissions, NH <sub>3</sub> slip, and the reducing agent consumption	NF	The geometry of the SCNR, Data from the plant	It is a typical calciner model for high-efficiency SNCR	The project had an end goal of limiting the NOx/NH <sub>3</sub> levels and achieving the target
14	[88]	Theoretical (CFD)	Emissions, Hot-Reburn Conditions	Coal, Petcoke, and other Alternate fuels	Mass flow rates, Temperatures	It is an MI-CFD model based on an initial mathematical model	CO emissions increase with increased AF substitution. NOx emissions increase when medium to high volatile coal is replaced with low volatile fuel
15	[89]	Theoretical (CFD)	Pressure drop in pyro-processing	Coal	Mass flow rates, Temperatures, Pressures	MI-CFD model of an inline calciner	The pressure losses of pyro-processing can be reduced, enabling either increased clinker production or reduced power consumption
16	[90]	Theoretical (CFD)	Emissions from the calciner outlet	Coal, Petcoke, AF1, and AF2	Composition of the fuels, Flow rates, Temperature	MI-CFD model of a separate line calciner	Petcoke showed the highest NOx and SOx emissions, followed by AFs and coal

Table 3 (continued)

Sr. No	References	Type of model	Parameters studied	Fuel	Input data	Specifications of the model	Key findings
17	[77]	Theoretical (CFD)	NOx emissions	Coal and Petcoke	Clinker production (tpd), % firing in kiln/calcliner, Overall air–fuel equivalence ratio in calcliner and riser	A comparative study with two calcliner conditions is presented. In calcliner A, the raw material is fed to lower and upper calcliner vessels from the 4th and 3rd cyclone stages, respectively. The raw meal is fed to only the lower calcliner vessel from the 5th cyclone stage in calcliner B	The generation of NO from char-N oxidation and depletion of NO by char-C are the most significant contributors to NO formation and reduction
18	[76]	Theoretical (CFD)	Optimal TSR of High-carbon-ash	Coal, High-carbon-ash (HCA)	Inlet temperatures, Velocities, Mole fractions	The heat value of HCA was first determined using a drop test, and later a calcliner model was developed where HCA was fired in the chamber	TSR > 30% didn't give a satisfactory output
19	[91]	Empirical (Soft Sensor/ AI/ML)	Apparent degree of calcination	NF	Mass flow rate, Inlet and Outlet Temperature, Inlet and Outlet Pressure, and Tertiary air temperature	LS-SVM based ANN Model	The model showed a favourable learning ability. It also showed a satisfactory prediction accuracy
20	[92]	Empirical (Soft Sensor/ AI/ML)	Calcliner Outlet Temperature	Coal	Coal feeding and other field data from the plant	Regression model	The sliding mode control improved the efficiency of the outlet temperature calculated using the regression model
21	[93]	Empirical (Soft Sensor/ AI/ML)	Calcliner Outlet Temperature	Coal	Raw material feeding, Tertiary air temperature, Coal injection in the kiln inlet and main burner	Process control model	The accuracy in predicting the outlet temperature can be improved by utilizing the appropriate model
22	[94]	Empirical (Soft Sensor/ AI/ML)	Calcliner outlet temperature and oxygen content of the exhaust	Coal	Raw materials, coal-fed for furnace, coal-fed for kiln, rotary speed of kiln, and negative pressure of CI export	Artificial neural network (Heuristic dynamic programming)	ADHDP improves the system operation stability more effectively than manual operation. For a large scope of changed data, the proposed method can give a good performance on control

Table 3 (continued)

Sr. No	References	Type of model	Parameters studied	Fuel	Input data	Specifications of the model	Key findings
23	[82]	Empirical (Soft Sensor/AI/ML)	Raw meal decomposition ratio	Coal	Calciner temperatures, calcium oxide content, ferric oxide, and silica content	A combination of the Fuzzy Model, KL Divergence, and S kernel functions	Prediction of the raw meal decomposition rate within acceptable error limits
24	[95]	Empirical (Soft Sensor/AI/ML)	Recognizing working conditions to optimize the control of calciner and cooler	Coal	Calciner exit temperature, outlet temperatures of the cyclone reactors, pressure beneath the grate cooler	Different DCS manufacturers design DCS systems. (VB 6.0 programming)	A list of operating conditions has been identified
25	[96]	Empirical (Soft Sensor/AI/ML)	Calciner outlet temperature	Coal	Coal feeding, Raw Material Feeding, Quantity of tertiary air	Mathematical and Grey correlation analysis	The online switching model improved the efficiency of the mathematical model developed
26	[97]	Empirical (Soft Sensor/AI/ML)	Abnormal condition detection	Coal	Calciner temperature, 1st cyclone cone pressure	Statistical	The model can reduce the chances of cyclone five feed tube blockage
27	[98]	Empirical (Soft Sensor/AI/ML)	Calciner outlet temperature	Coal	Calciner coal feed, kiln head coal feed, raw material feed, and ID fan speed	Mathematical adaptive multi-dimensional Taylor network control (adaptive MTN)	Simulation results verify the effectiveness and feasibility of adaptive MTN
28	[96]	Empirical (Soft Sensor/AI/ML)	Calciner outlet temperature	Coal	Raw material feeding and coal feeding, tertiary air temperature	Single-Input and Single Output (SISO) and Multiple-Input and Single-Output (MISO) Models based on regression models	Out of all the developed models, the three inputs model showed the highest accuracy
29	[99]	Empirical (Soft Sensor/AI/ML)	NOx Emissions	Coal	Preheater fan speed, calciner outlet temperature, kiln tail pressure, kiln coal feeder, kiln head pressure, kiln head temperature, grate cooler pressure	Just-In-Time Gaussian (JIT) Mixture Regression	Integrating the JIT model improved the efficiency and accuracy with which the emissions were predicted
30	[100]	Empirical (Soft Sensor/AI/ML)	The efficiency of the hybrid model developed	Coal	Calcination outlet temperature, kiln speed	ANFIS model coupled with a hybrid clustering algorithm	A hybrid clustering algorithm is more efficient and accurate when compared to FCM and Subclust algorithms

heavy coating layers in the kiln with RDF as AF. The study concluded that the thick coating in the sintering zone would change the kiln temperature profile and shift it towards the kiln inlet. It will decrease the RDF residence time in the gas phase leading to smaller alite with high free lime in clinker. Pieper et al. [110] also simulated rotary kiln using 1 D model in CFD considering the coupling of gas phase and solid bed. 50% RDF and 50% lignite are the fuel mix. The results indicated a narrow flame shape, lower gas temperature in the sintering zone, and lower alite and high free lime in the clinker. One paper reported that the plants operating at high % TSR through RDF with petcoke as the primary fuel are facing coating problems in the kiln refractory lining. RDF ash with high chloride and alkalis is combined with petcoke sulfur, resulting in coating formation [111].

In view of above, it can be said that RDF coprocessing in kiln/calcliner is feasible. However, some impacts are inevitable, which needs some modification in the system. For calcliner, several pre combustors are available to achieve high TSR through calcliner. FLS hot disc, Polysius step combustor, and KHD pyro rotor are some of them. Already seven pyro rotors are installed in cement plants for AF co-processing, where the retrofit is done in calcliners helping in production increase with reduced emissions [69]. Hot disc technology can be employed where a wide variety of coarse alternative fuels like RDF, whole tyres are fired in calcliner [67]. The prepol step combustor has a static combustion grate with fuel retention time of 15–20 min for drying and igniting alternative fuel like RDF [68]. With all these technologies, cement plants can achieve high TSR in calcliner; however, no such technology is still available for kiln burners. Hence TSR in the kiln burner is lagging. A breakthrough in pre-combustion technology is required to improvise AF firing through the kiln burner.

## RDF Gasification

Gasification transforms feedstock like biomass, RDF, etc., into syngas rich in hydrogen and carbon monoxide [112]. Gasification occurs in a reducing environment requiring heat, whereas combustion occurs in an oxidizing environment releasing heat [113]. There are different types of gasifiers like fixed bed, fluidized bed, and entrained flow gasifiers depending upon gas–solid contacting pattern, each having its own merits and demerits [114–116]. The performance evaluation is based on higher heating value ( $\text{MJ}/\text{Nm}^3$ ), cold gas efficiency, hot gas efficiency, carbon conversion efficiency, equivalence ratio, etc. [113, 117]. Several thermodynamic, kinetic, ANN, CFD, and process simulation models have been developed for gasification. Silva et al. [118] described thermodynamic equilibrium models for biomass gasification. Vázquez et al. [119] compared stoichiometric and

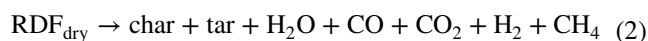
non-stoichiometric models using ASPEN PLUS software. A dynamic model, incorporating the mass and energy transport with the kinetics of wood gasification, was developed by Patra et al. [120]. Patra and Sheth [121] reviewed different models for downdraft gasifiers such as thermodynamic equilibrium, kinetic, CFD, ANN, and ASPEN Plus models. A comparative analysis of each model and its output is carried out. Yan Yang et al. [122] reviewed the recent progress in RDF gasification/co-gasification in detail, covering modelling, experimentation, and economic aspects. Seo et al. [123] studied MSW gasification mechanism, technologies, operating and performance parameters like equivalence ratio, reactor temperature, residence time, etc., and environmental impacts. Very few experimental results have been reported on RDF gasification. Rao et al. [124] performed experimental runs for RDF pellets on an updraft gasifier. Syngas obtained was having a CV of  $5.59 \text{ MJ}/\text{Nm}^3$  with a cold gas efficiency of 73%. Khosasaeng and Suntivarakorn [125] achieved a syngas heat value of  $5.87 \text{ MJ}/\text{Nm}^3$  from RDF gasification with cold gas efficiency of 73% at an equivalence ratio of 0.35 with air as the gasifying agent. Dalai et al. [67] gasified 1 g RDF fluff and RDF pellet in a fixed bed reactor. The results reported that higher C and H content produce syngas with high  $\text{H}_2$  and CO content. The effect of different steam to waste ratios were studied, and it concluded that 2 is the optimum value for syngas yield.

There are several steps in RDF gasification, including drying, pyrolysis, combustion, and gasification. Combustion of fuel occurs in a sub-stoichiometric environment in the combustion zone and the heat liberated during combustion derives from the drying, pyrolysis, and reduction zone endothermic reactions as mentioned in Eq. 1–7.

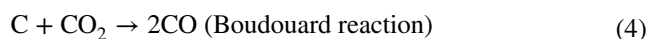
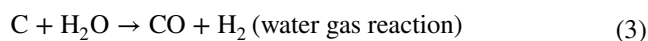
The first stage is heating and drying at about  $160 \text{ }^\circ\text{C}$ , in which moisture is removed from the feedstock.

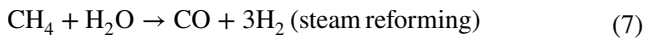
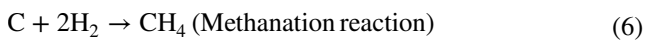
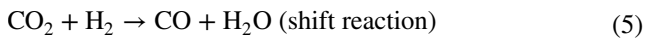


The second stage is pyrolysis around  $400\text{--}700 \text{ }^\circ\text{C}$  in the absence of oxygen. Thermal cracking reactions and gases such as  $\text{H}_2$ , CO,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{H}_2\text{O}$  and  $\text{NH}_3$ , tar (condensable vapours), and char as the residue is liberated. Vapours produced in this stage undergo thermal cracking to gas and char.



The next step is gasification, a chemical process in which char reduction is predominant through various chemical reactions in the temperature range of  $800\text{--}1000 \text{ }^\circ\text{C}$  [121].





The resulting syngas contains  $\text{H}_2$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{C}_x\text{H}_y$  [126].

There are recent developments in gasification technologies. An oxy-gasification technology has been developed to gasify any waste, including batteries, medical waste, etc., into high-quality syngas with oxygen and steam as gasifying agents [127]. To reduce the heterogeneity effect of RDF and improve syngas quality, several researchers in the recent past have studied the co-gasification of RDF with biomass. Pio et al. [128] demonstrated co-gasification of RDF with pine pellets in an 80 kWth pilot-scale bubbling fluidized bed reactor. The lower heating value of syngas increased by 10% compared to 100% RDF, which is significant in terms of economic viability. Burra and Gupta [129] studied the co-gasification of biomass and plastics in a semi-batch reactor in which  $\text{H}_2$  content got enhanced by three times the individual gasification. Still, a lot of biomass materials can be explored for co-gasification with RDF. Steam gasification can be a boon for cement plants having captive power plants where waste steam can be used for gasification purposes. Galvagno et al. [130] conducted an experimental study of RDF gasification with steam in a bench-scale rotary kiln reactor. Trial runs were conducted in a temperature range of 850–1050 °C in a gasifier with a proper syngas purification system with different syngas applications. The next section focusses on the integration of gasification in the cement industry.

## Integration of Gasification in the Cement Industry with Different Configurations

The share of global syngas output is 61% from coal, 29% from petroleum, 7% from gas, 2% from petcoke, and only 1% from biomass, and almost no contribution from RDF waste [131]. Syngas applications include waste management, biofuel production (e.g., FT kerosene), hydrogen production, refinery integration, etc. Recent trends indicate interest in syngas production from RDF waste via gasification and can be used as an alternative fuel in the cement industry. An onsite gasification plant is needed to use the syngas in the cement plant. Few researchers have reported the integration of the gasification process with cement plants. The process integration aspects need to be explored to achieve the perfect integration strategy.

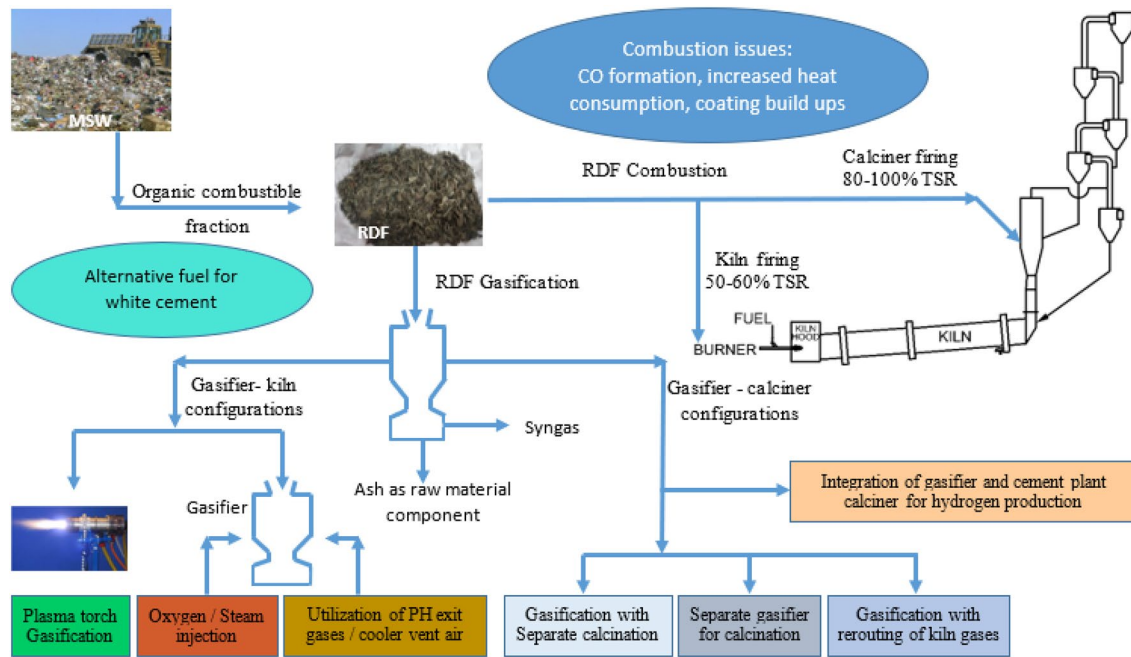
Chatterjee et al. [132] studied three working models for co-processing of MSW in China; (a) Sinoma model, which

involves direct pre-treatment and co-processing, (b) Conch model considering gasification pre-treatment and co-processing (c) Huaxin model, which refers to fermentation pre-treatment and co-processing. Each model has its own merits and demerits. In the conch model of MSW gasification, gasification takes place in a fluidized bed furnace to obtain syngas as an alternative fuel, and ash discharged from the bottom is utilized as a raw material in cement. However, the Sinoma model is reported to perform better. A 450 tonnes per day MSW-based facility for a cement plant capacity of 5000 tonnes per day clinker based on the Sinoma model was set up in 2013 in China. Wang [133] studied the Jinyu model of RDF thermal treatment focused upon RDF quality for co-processing in cement kilns. MSW is pretreated to produce low-quality and high-quality RDF. High-quality RDF having CV more than 2500 kcal/kg with moisture less than 30% and particle size less than 50 mm is directly combusted in cement plants. However, low-quality RDF undergoes pyrolysis, gasification in a vertical rotary gasifier, and syngas obtained is sent to the kiln system. Greil et al. [134] were the first group who reported the implementation of integration of gasification in the cement plant of 5000 tpd capacity. A circulating fluidized bed gasifier is installed with shredded wood as feedstock, which provides the syngas to the calciner. At the same time, the burnt-out ash is fed to the raw mill acting as a raw material component, thus no waste generation through the process.

Calcined clay activation is another area where gasifier integration is possible to produce the calcine clay-based cement. Pinho et al. [135] reported that clay activation at 700–900 °C can be done in a gasifier in a sub-stoichiometric air environment. Several configurations utilizing the concept of waste heat recovery, air preheating, oxy-fuel gasification lime as sorbent for hydrogen production in comparison to RDF combustion have been shown in Fig. 4 and discussed in Sections “Configurations for syngas firing in the calciner”, “Configuration for syngas firing in the kiln only”, and “Configuration for syngas firing in the kiln and calciner both for syngas firing in kiln/calciner”.

## Configurations for Syngas Firing in the Calciner

Hjuler [136] reported two different configurations (*A* and *B*) for syngas firing in the calciner involving the recirculation of kiln exhaust gases and  $\text{CO}_2$ -based gasification with a waste heat recovery system. Wensan et al. [137] demonstrated separate waste gasification integrated into the calciner of the pyro-processing system as discussed in the configuration *C*. Schuermann et al. [138] explored the utilization of kiln exhaust gases in gooseneck type gasifying reactor through configuration *D*. Gasifier is integrated further with calciner



**Fig. 4** RDF combustion vs gasification integration in cement industry

to utilize syngas as fuel in the calciner. Weil et al. [139] presented configuration *E* on how to enhance hydrogen production through gasification by consuming calcium oxide produced during limestone calcination in clinker production without affecting the latter. These configurations *A* to *E* are discussed in detail in the next section.

### Configuration A

Figure 5 describes configuration *A* of the integrated system of calciner and gasifier [136]. This system discusses different concepts such as raw meal calcination, waste heat recovery maximization for power generation, and gasification integration. In this system, calciner exhaust hot gases (around 900 °C) is utilized for fuel gasification in a gasifier to obtain syngas. The syngas is sent to calciner as an alternative fuel for calcination purposes. Initially, the raw meal gets heated in a preheater by utilizing hot gases and enters the calciner. Calcined material is split into two streams; one stream is fed to the kiln for further clinkering reactions. The other stream is sent to the riser duct, which receives kiln exhaust gases and supplemented with secondary fuel and air for further combustion. The idea is to raise the calcined material's temperature further and send it back to the calciner, where it can transfer heat for raw meal calcination. It will eliminate the use of direct solid fuel combustion in the calciner. Exhaust gases from the riser duct are sent to the preheater for material preheating purposes. It is entirely different from the typical case where high-temperature kiln exhaust gases enter

the calciner through the riser duct. Further calciner exhaust gases are sent to the preheater, which is used for preheating the raw meal. Different scenarios of calciner exhaust gas recirculation are explored for this purpose.

### Configuration B

Figure 6 describes configuration *B* of the integrated system of calciner and gasifier [136]. Integration proposed in this configuration is based on the carbon capture for clinker production as CO<sub>2</sub> is circulated in the system with waste heat recovery. CO<sub>2</sub> is used as a gasifying agent in the gasifier, and produced syngas is fed to the calciner. It is combusted with pure O<sub>2</sub>. Calciner exhaust gases containing mainly CO<sub>2</sub> are utilized to generate power, and low-temperature turbine exhaust with CO<sub>2</sub>-rich vapour is recirculated to clinker cooler. It replaces ambient air for clinker cooling purposes. Water/water vapour is added to the cooler to adjust CO<sub>2</sub> concentration. The CO<sub>2</sub> takes up the recuperated heat from the clinker and enters the gasifier with solid/liquid tertiary fuel. Syngas thus obtained after gasification along with O<sub>2</sub> are used for the calcination of raw meal. The rest of the process of the material split to kiln and riser duct and further recirculation of material to calciner is similar to configuration *A*.

### Configuration C

Figure 7 describes configuration *C* of the integrated system of calciner and gasifier [137]. This system proposes



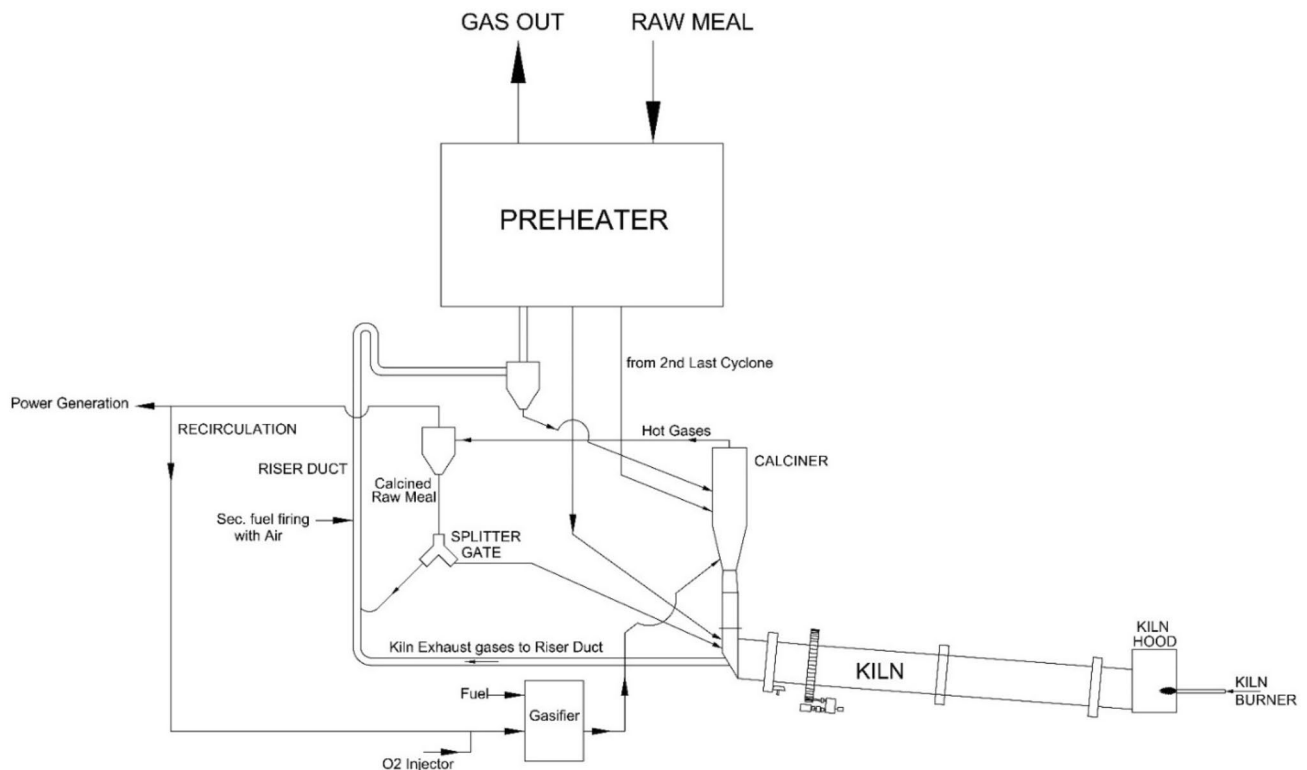


Fig. 5 Gasification with separate calcination- configuration A [136]

gasification for different calciner configurations like inline calciner, separate line calciner, and without calciner. Household waste, industrial waste, including waste plastics having a calorific value of 1000–3000 kcal/kg, is gasified in a fluidized bed gasifier to generate syngas as a fuel. The gasifier is also supplied with auxiliary fuel (scrap tires, charcoal, wood chips, etc.) to maintain the temperature inside around 500–600 °C. Air is supplied from blower to gasifier for fluidization purposes. The incombustible material settles with fluidizing sand at the bottom of the gasifier and is separated through a classifier. Sand is transported back to the gasifier while the ash containing metallic components is utilized as raw material for clinker manufacture.

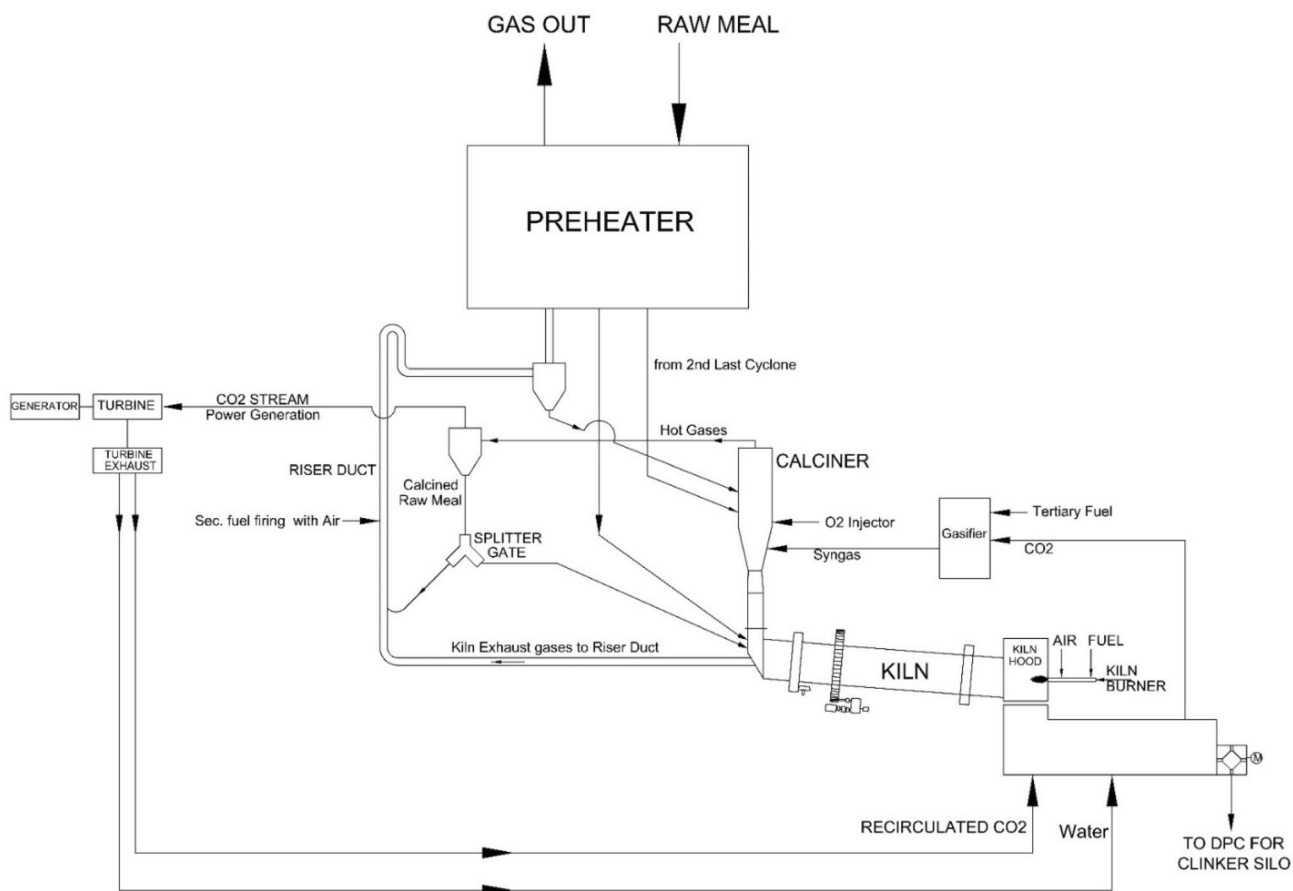
The temperature inside the calciner is more than 800 °C with a residence time of more than two seconds which may be sufficient for the complete combustion of syngas. The negative pressure is maintained in the calciner, which helps draw syngas from the transport line. A bypass line from the kiln inlet has also been considered to control chloride and alkali concentration during gas circulation in the preheater. A detailed computational fluid dynamics (CFD) simulation was done for syngas as partial fuel replacement in the preheater with or without calciner. The ratio of a flow rate of syngas over the flow rate of kiln exhaust gas was established by simulation along with prediction of the amount of gas generated in the gasifier ( $\text{Nm}^3/\text{hr}$ ), CO concentration in the

calciner, the gas pressure in the calciner (kPa) & gasifier and flow rate ratio of syngas /kiln exhaust gas, etc.

### Configuration D

Figure 8 describes the configuration *D* of the integrated system of calciner and gasifier [138]. This configuration incorporates a new way of integrating gasifying furnaces in the clinker manufacturing process using process gases inside the kiln system. The two energy-intensive reactions in clinker manufacturing are calcination at 800–850 °C and clinkering at around 1450 °C.

An inverted U shape gasifying furnace is employed to pyrolyze the fuels and is located between the calciner and kiln. The kiln exhaust gas flow path and the outlet of the gasifier are connected above the tertiary airline. Fuel gasification takes place in a gasifier in the presence of kiln exhaust gas at high temperature along with a portion of tertiary air from cooler. Syngas produced travel to calciner and act as a fuel. Syngas get burnt in calciner in the presence of balanced tertiary air to provide heat for raw meal calcination. Tertiary air is split between calciner and gasifier using an adjustable flap valve. The calciner has a swirl chamber for completely burning gasifier syngas and optional fuel injection into the calciner.



**Fig. 6** Gasification with separate calcination- configuration B [136]

Streit and Feiss et al. [140] highlighted the particular type of calciner developed by KHD recently named Pyroredox. A gasifier is connected upstream to the calciner, and the gasification zone is separated from the oxidation zone. Gasifier best uses Boudouard reaction, reducing NO<sub>x</sub> emissions without impacting production and specific heat consumption in cement plants.

### Configuration E

Figure 9 describes the configuration E of the integrated system of calciner and gasifier [139]. This configuration involves a unique concept in which the focus is on enhanced separate hydrogen production taking advantage of the cement manufacturing process. Hydrogen will be the future fuel; hence its production in different ways is an ongoing research process. Thermal gasification of waste to obtain hydrogen is one of them. The removal of nitrogen and carbon dioxide from syngas enhances hydrogen concentration. Some sorbents like CaO are useful, leading to in-situ CO<sub>2</sub> capture by forming calcium carbonate after reacting with carbon dioxide. It is produced by dissociating calcium

carbonate by the calcination process, which is energy-intensive. This calcination is a crucial process in cement production, and here lies the opportunity for hydrogen production where this linkage can gainfully utilize lime from calcined material.

During clinker manufacturing, the raw meal enters the preheater at 40–50 °C and then undergoes preheating to reach 750–850 °C until the second lowermost cyclone before entering the calciner. The material gets 30–40% calcined in the preheater and achieves 85–90% calcination before entering the kiln for further reactions. Hot pre-calcined meal from the second lowermost cyclone is supplied as a heat source for the gasifier placed in parallel through a siphon where fluidization is done by superheated steam. Fuel fed to gasifier undergoes drying and pyrolysis at a temperature of approximately 650 °C after contacting pre-calciner raw meal. The cracking of tar occurs in the presence of steam in an upper zone of the gasifier. The catalytic activity of CaO also enhances it. The gas composition changes with enriched hydrogen after the removal of CO<sub>2</sub>. The unburnt char/ash/coke and carbonated meal obtained from the gasifier bottom at

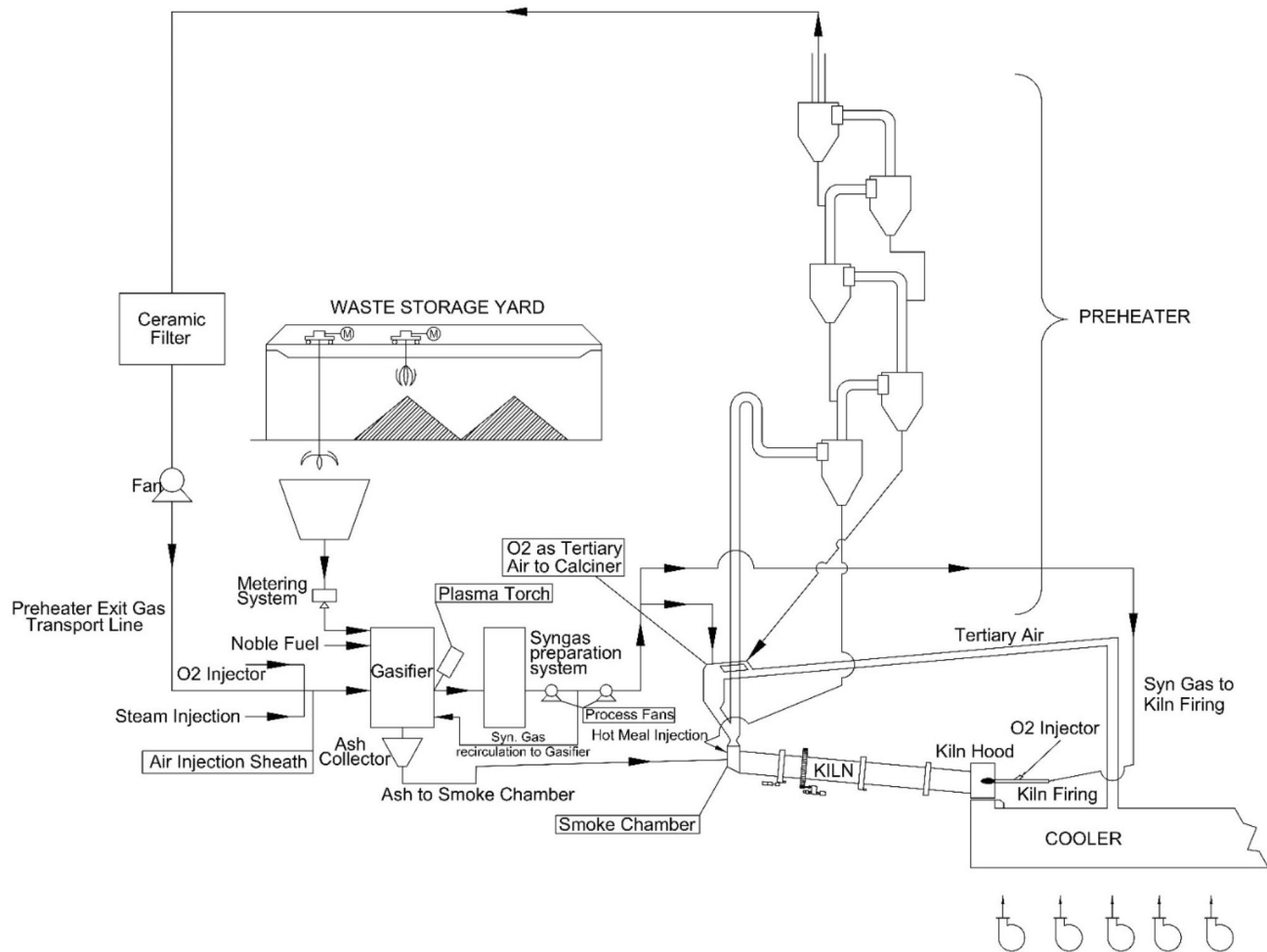


Fig. 7 Separate gasifier for calcination- configuration C [137]

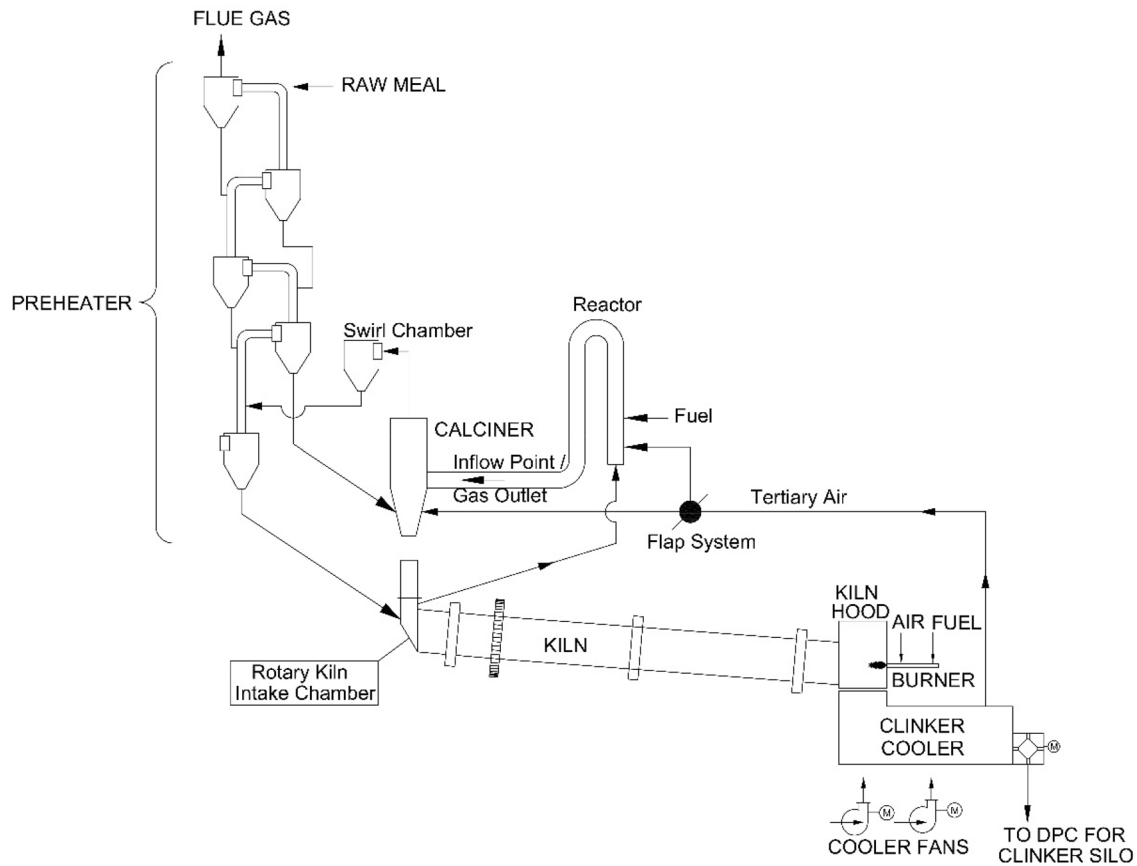
600 °C are recirculated back to the calciner, where the carbonated meal is heated further to more than 850 °C for calcination. Coke burnt in the presence of air is a source of heat. A calcined meal from the last cyclone enters the kiln. The downstream of the gasifier consists of a gas cleaning unit that removes the impurities like chlorine, sulfur, and mercury. Further, the gas is fed into a pressure swing adsorption (PSA) unit for hydrogen separation. The tail gas obtained can be used as a fuel substitute for the calciner for heat recovery.

### SWOT Analysis of Various Configurations

All five calciner configurations have some pros and cons. SWOT analysis has been done in Table 4 to illustrate the advantages, disadvantages, configuration improvement points, and applicable circumstances for each configuration.

### Configuration for Syngas Firing in the Kiln Only

The applicability of syngas as an alternative fuel in cement rotary kiln depends on its calorific value and the level of impurities. Syngas mainly contains hydrogen and carbon monoxide. As per literature, hydrogen alone could not be used as an alternative fuel in cement rotary kilns due to its explosive properties combined with different combustion and radiation properties. But dilution with other gases like  $N_2$  or steam can make it useable in the future [141]. A recent investigation showed that hydrogen can be used along with biomass in a kiln burner and will support overcoming the low calorific value limitation associated with high levels of biomass usage [142]. To the best of the authors' knowledge, no literature is available for syngas utilization as the primary fuel in cement rotary



**Fig. 8** Gasification reactor using kiln gases for gasification- configuration *D* [138]

kiln where the temperature required in the burning zone is 1300–1450 °C for clinkerisation reaction.

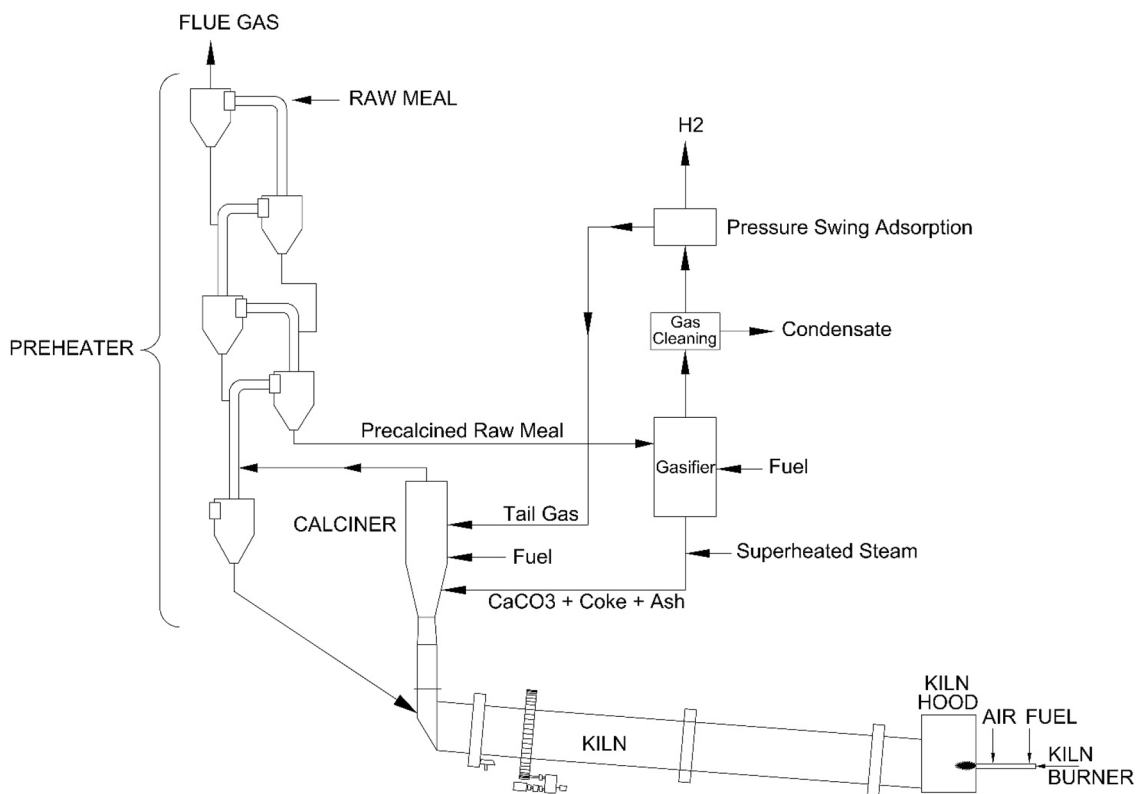
Researchers have reported syngas application in lime kiln plants where the temperature required is around 800–900 °C for calcination purposes. Talebi and Goethem [143] investigated a plasma gasifier performance fed with RDF to generate syngas with a 0.82 mass ratio of plasma gas to feedstock. Syngas clean-up technologies were applied before using them in the kiln. The desired calcination temperature is attainable since the adiabatic flame temperature of syngas is higher than that of coke oven gas (current fuel for the lime kiln). But the low heat value of syngas increases the fuel quantity requirement, which needs system modification.

### Configuration for Syngas Firing in the Kiln and Calciner Both

Figure 10 shows the configuration of the integrated system for kiln and calciner with gasifier [144]. To achieve complete waste utilization in clinker production, the kiln and calciner must be fed with alternative fuels. As discussed in the previous section, the kiln fuel firing requirement is more

specific, making 100% waste utilization quite challenging. Hue et al. [144] illustrated the gasification integration concept in cement plants considering 100% syngas as fuel for kiln and calciner. To achieve this, high NCV with minimum impurities is the precondition. Some of the ideas presented in the patent for enhancing the NCV of syngas along with an increase in the energy efficiency of gasifiers are (a) the utilization of preheater exit gases available at more than 250 °C in the gasifier, (b) quaternary (heated) air from clinker cooler at gasifier inlet can be utilized, (c) injecting O<sub>2</sub> into the gasifier, reducing nitrogen impact, (d) steam injection into a gasifier, and (e) enrichment of C by addition of noble fuel (coal, petcoke) along with the waste. Syngas obtained from the gasifier is sent to the syngas purification unit to remove tar, chlorine, sulphur etc. The purified syngas is fed as fuel to calciner and kiln in a pre-defined ratio. Plasma torch gasification is proposed between gasifier and syngas purification unit, which cracks tar into smaller condensable molecules at very high temperatures.

In this system, waste from the storage yard is sent to the gasifier via the metering system. Some noble fuel (coal, petcoke) shall be fed along with waste to increase carbon content. Air is used as a gasification agent for the purpose. The



**Fig. 9** Integration of gasifier and cement plant calciner to enhance hydrogen production—configuration E [139]

preheater exit gases or cooler vent air can be provided instead of ambient air. Steam/O<sub>2</sub> also can be utilized to increase heat value. A calciner is provided with two tertiary air ducts for O<sub>2</sub> and air, respectively. Oxygen injection is done at the kiln outlet also to improve combustion inside the kiln. Raw meal after preheating in preheater from 60 °C to 800 °C is calcined in the calciner and enters the kiln through the hood for clinker reactions. Heat for calcination at ~850 °C and clinkerisation at ~1450 °C with flame temperature > 2000 °C is supplied by gas firing. The rest of the system will not change. Ash from the gasifier is collected at the bottom and sent to the smoke chamber where some unburnt carbon present in ash got burnt, and that heating value can be utilized for combustion purposes.

Another way of ash utilization is an alternative raw material. Ash collected is ground with other raw materials and sent to the preheater as feedstock. It will help in the utilization of mineral components present in ash as feedstock for clinker manufacture. A schematic diagram indicating ash utilization as cement raw material is shown in Fig. 11.

### Remarks on the Configuration of Syngas Firing in the Kiln

Oxygen use instead of the air shall be uneconomical due to energy-intensive air separation techniques employed as per

past experiences. Similarly, the plasma torch done at a very high temperature is highly energy-intensive. Hence this technology does not look promising to be applied soon. It can become viable only when there is some economical option for an energy source for oxy gasification and plasma torch. H<sub>2</sub> as a part fuel has been explored but is still at a nascent stage. The design must be modified accordingly for 100% H<sub>2</sub> utilization in the kiln, which is a potential area of future research. Renewable H<sub>2</sub> will be an asset in this case.

### Future Scope

The domain which is left unexplored for syngas utilization in the cement industry is kiln bypass systems. Many plants worldwide operating at high TSR with difficult waste have kiln bypass systems. A portion of kiln inlet dust-laden gases is extracted to avoid buildups, and coatings in the preheater and kiln. Two Indian cement plants have recently installed kiln bypass and they are operating at 30% TSR using RDF as the main alternative fuel in the calciner. Hence, in the future, there may be a kiln bypass requirement when plants are operated at high TSR. High-temperature gases at around 1000 °C and semi calcined material having high chloride/alkali may be available in

**Table 4** SWOT analysis of calciner configurations

Configuration	Strength	Weakness	Opportunities	Threats
A	<ul style="list-style-type: none"> <li>Enhanced waste heat recovery for power generation due to availability of calciner exhaust gases at high temperature</li> <li>Calciner exhaust gases utilization for gasification will reduce the fuel requirement of the gasifier</li> <li>Reduction in carbon footprint</li> <li>Decrease in fossil fuel consumption in the calciner</li> </ul>	<ul style="list-style-type: none"> <li>Calciner exhaust gases may contain SO<sub>x</sub> and NO<sub>x</sub> which can impact gasifier operation</li> <li>Major retrofit required in the kiln system</li> <li>Water addition to clinker cooler for CO<sub>2</sub> adjustment will lead to increased water consumption in pyro processing</li> </ul>	<ul style="list-style-type: none"> <li>Establishing syngas as an alternative fuel in the calciner</li> <li>Establishing syngas as an alternative fuel in the calciner</li> <li>CO<sub>2</sub> is circulated in the system for waste heat recovery, thus reducing CO<sub>2</sub> emissions by up to 50%</li> <li>Establishment of Carbon capture technology</li> <li>Establishing syngas as an alternative fuel in the calciner</li> <li>High heat value of syngas by O<sub>2</sub> injection, steam injection or plasma torch gasification</li> </ul>	<ul style="list-style-type: none"> <li>A split of calcined meal in the riser duct and kiln is critical and may result in operational issues</li> <li>Lack of experience in gasifier operation</li> <li>O<sub>2</sub> injection requires separation of O<sub>2</sub> from air which can be unviable</li> <li>Rest of the CO<sub>2</sub> to be sent underground</li> </ul>
B	<ul style="list-style-type: none"> <li>No major retrofit is required as the gasifier is a separate unit to be integrated with the calciner</li> <li>Ash containing metallic components can be utilized as raw material for clinker manufacture</li> </ul>	<ul style="list-style-type: none"> <li>Air at ambient temperature as a gasifying agent is to be heated, leading to high energy consumption</li> </ul>	<ul style="list-style-type: none"> <li>Advantage of utilizing kiln gases with optimum O<sub>2</sub>% in the gasifier</li> </ul>	<ul style="list-style-type: none"> <li>Plasma torch gasification/O<sub>2</sub> injection is energy-intensive thus may be unviable</li> </ul>
C	<ul style="list-style-type: none"> <li>Reducing conditions created in gasifiers due to kiln gases will help in controlling NO<sub>x</sub> emissions too, which is a major issue for the cement industry</li> <li>Minimal chance of bulky fuels falling down the calciner</li> </ul>	<ul style="list-style-type: none"> <li>Gasifier ash cannot be separated as it becomes an integral part of the kiln system due to kiln gases in the gasifier</li> <li>Tertiary air split between gasifier and calciner is critical</li> <li>Operational problems in calciner are expected due to the re-routing of kiln gases previously used for maintaining gas velocity to prevent material from falling directly into the kiln</li> </ul>	<ul style="list-style-type: none"> <li>Advantage of utilizing kiln gases with optimum O<sub>2</sub>% in the gasifier</li> </ul>	<ul style="list-style-type: none"> <li>Fuel firing location and syngas velocity are critical considering material lifting in the calciner</li> </ul>
D	<ul style="list-style-type: none"> <li>Both gasification technology and pyro-processing adopt benefits of each other</li> <li>Elimination of the sorbent regeneration step for gasification</li> <li>Elements like MgO or Fe show catalytic activity related to tar decomposition</li> <li>Fuel ash from gasifier can be used as alternative raw material for cement production</li> </ul>	<ul style="list-style-type: none"> <li>Hydrogen utilization as an alternative fuel in the cement industry is still at the research stage</li> <li>Storage, transport, safety, utilization, and scale-up issues for hydrogen utilization</li> </ul>	<ul style="list-style-type: none"> <li>Cement plants can become self-reliant for hydrogen production as a fuel</li> <li>Potential to reduce fuel combustion and CO<sub>2</sub> emissions since hydrogen is a clean fuel</li> </ul>	<ul style="list-style-type: none"> <li>Availability of superheated steam in cement plant</li> <li>The degree of calcination will reduce as pre calcined material entering the gasifier from the second last cyclone gets converted to CaCO<sub>3</sub> which will also undergo calcination in the calciner</li> </ul>
E				

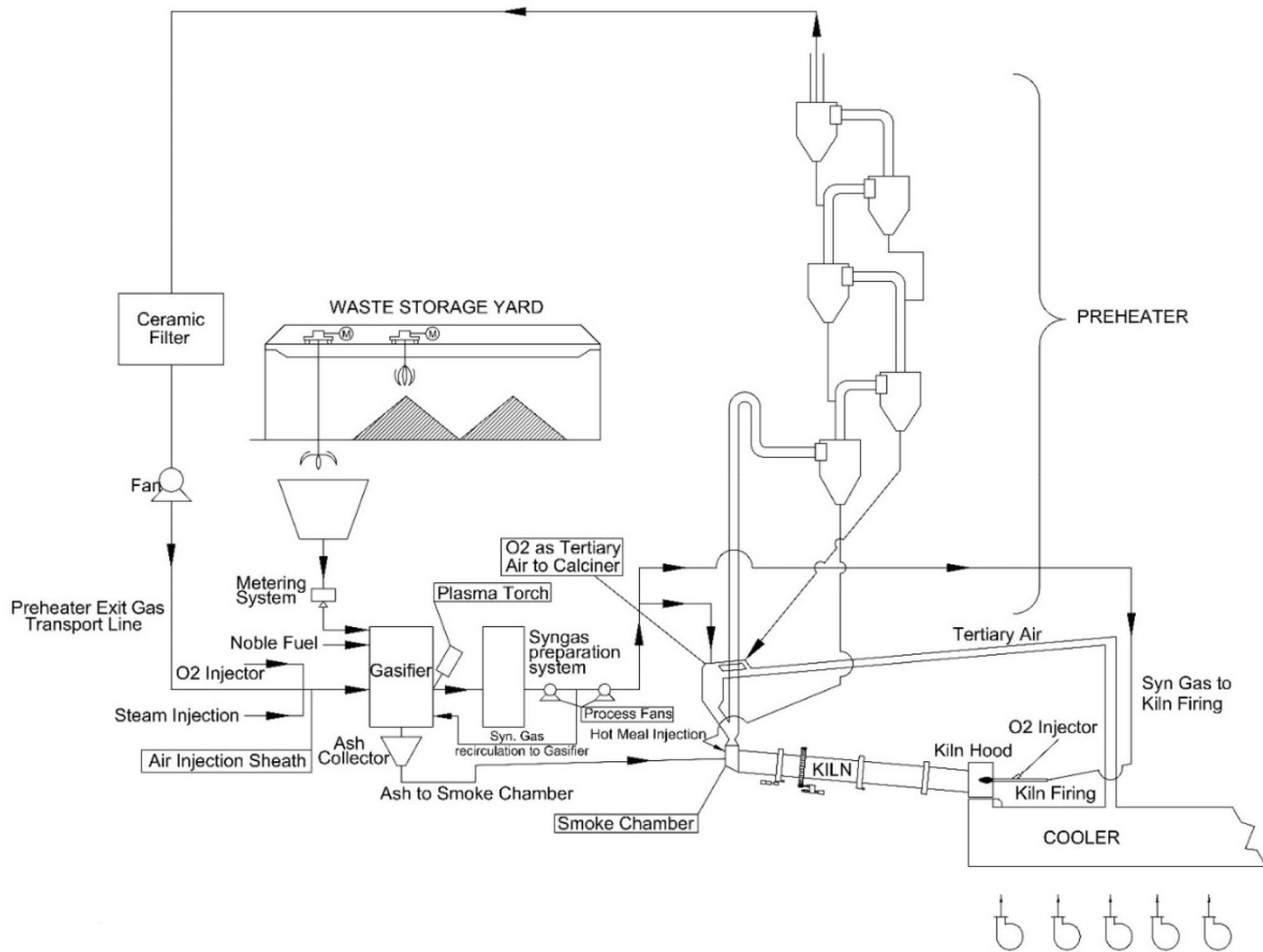


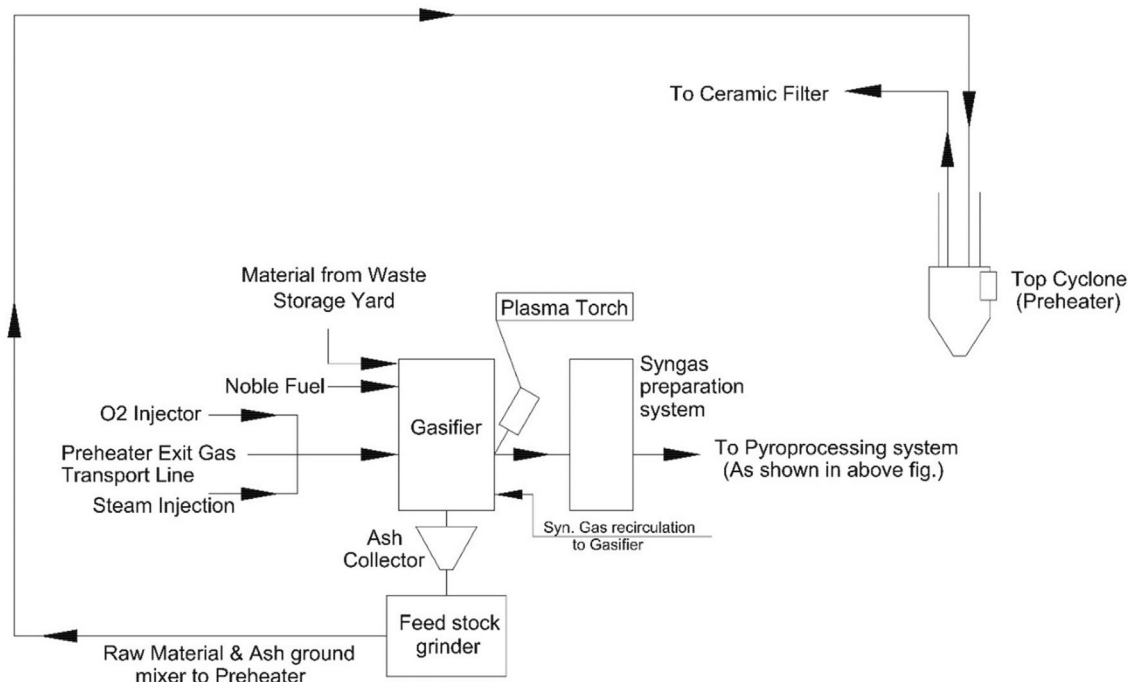
Fig. 10 High-quality syngas from waste gasification for pyro-processing [144]

the future. The reusability of dust-laden gases for gasification is unexplored and opens a school of thought for researchers. The bypass material recirculation, bypass gas purification, and optimal use of tertiary air/cooler air/kiln exhaust air need a thorough investigation to achieve high efficiency during gasification.

Future research should also be dedicated to increasing the heat value of syngas by different means such as steam gasification, oxy-gasification, and preheated air to co-process syngas in cement rotary kiln where a minimum 4000 kcal/kg fuel heat value is required. One promising area of research is the feasibility of RDF gasification for white cement as no alternative fuel is established due to the impact of fuel ash on whiteness. Due to petcoke gasification plants producing the value-added products, its availability will be an issue for the white cement [145]. Another research area is the utilization of ash obtained from gasifiers during RDF gasification as cement raw material.

## Conclusions

The article highlights the recent advancements in RDF direct firing in kiln and calciner in comparison to the futuristic technology of RDF gasification. The article emphasized that the issues related to RDF particle size, ash content, high chloride content, and inconsistent heat value can be tackled by RDF gasification, particularly in white cement plants where no alternative fuel is established. It can be stated that biomass gasification is matured while RDF gasification is still at a nascent stage. The major drawback is the low heat value of syngas obtained from RDF gasification which necessitates the high gas volume making it unviable for process applications. RDF gasification necessitates input moisture to be less than 20% while Indian RDF contains moisture in the range of 35–40%. An extensive review of different configurations



**Fig. 11** Gasifier ash utilization as a raw material component for clinker manufacture [144]

of kiln/calciner with gasifier for gasification applicability to the cement industry, kiln/calciner direct combustion models, and pilot studies will lead to the development of suitable models for calciner and gasifier as a single unit. The different gasification integration technologies with varied configurations for cement plant calciner (A–E) are discussed in detail. It was concluded that co-processing of syngas in cement plant calciner is technically feasible while in the kiln, it requires changes in kiln design due to syngas properties. Configuration C, where a separate gasifier is envisaged to provide syngas to calciner, is the suggested technology out of all the configurations. Moreover, if chloride pretreatment is adopted during gasification, the TSR can increase tremendously without impacting plant operation, which is unviable without a kiln bypass during RDF combustion.

**Author Contributions** BNM had the idea for the article, PS performed the literature search, process & data analysis, and drafted the article and PNS critically revised the work.

**Funding** The authors have not disclosed any funding.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

## References

1. US Geological Survey: Mineral Commodity Summaries, pp. 204–205. Reston, VA (2020). <https://doi.org/10.3133/mcs2020>
2. Sada Sahu, Vahit AtakanKalbfleisch, B. Low-CO<sub>2</sub> synthesis SCMs. *International cement review*, (2021). 9, 1–3. [https://assets.ctfassets.net/jv4d7wct8mc0/4Mix11YBEqDwa0UbDVVbjv/3ba7c868b430867fa6be191a5a9d7e65/ICR\\_REPRI\\_NT\\_2021-09\\_Solidia\\_Technologies\\_LR.pdf](https://assets.ctfassets.net/jv4d7wct8mc0/4Mix11YBEqDwa0UbDVVbjv/3ba7c868b430867fa6be191a5a9d7e65/ICR_REPRI_NT_2021-09_Solidia_Technologies_LR.pdf).
3. India Brand Equity Foundation Cement: <https://www.ibef.org/download/Cement-June-2020.pdf>. Accessed 18 Oct 2021
4. Ministry of commerce & industry, Eight Core Industries (ICI): Department for promotion of industry and internal trade. (2020)
5. Jiaosheng, Q., Yuansheng, C. Guiping, T.: Checking in on China. *World Cement*, May ed. (2020). 12–20. <http://publications.worldcement.com/flip/world-cement/2020/May/hd3kk.html#1>.
6. International energy agency: Technology Roadmap Low-Carbon Transition in the cement industry. IEA (2018). pp. 5,29. <https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Technology-Roadmap-Low-Carbon-Transition-in-the-Cement-Industry>.
7. Sonebi, M., Ammar, Y., Diederich, P.: Sustainability of cement, concrete and cement replacement materials in construction, pp. 371–396. *Sustainability of Construction Materials*. Woodhead Publishing, Swaston (2016). <https://doi.org/10.1016/B978-0-08-100370-1.00015-9>
8. Confederation of Indian Industry: Case study manual on alternate fuels & raw material utilization in Indian cement industry (2011). pp. 1–90. <https://shaktifoundation.in/wp-content/uploads/2017/06/afr-utilisation-in-cement-industry-final-10-jan-2012.pdf>.



9. Brannvoll, F. Vasyutenko, M.: *World markets, energy and freight update*. In: *International Cement Conference Cemtech*. (2020)
10. Ambuja Cements Limited: *Sustainable development report*, (2019). Pp. 41–42 [https://www.ambujacement.com/Upload/PDF/Ambuja-SD-Rep\\_11820\\_WEB.pdf](https://www.ambujacement.com/Upload/PDF/Ambuja-SD-Rep_11820_WEB.pdf)
11. ACC Limited: Sustainability Report S. Adsvita.: pp. 49–50 (2018). [https://www.acclimited.com/assets/new/pdf/ACC\\_Sustainable\\_Development\\_Rep2018-Aug5\\_2019.pdf](https://www.acclimited.com/assets/new/pdf/ACC_Sustainable_Development_Rep2018-Aug5_2019.pdf)
12. Ernst & Young Associates LLP: Ultratech Cement Limited Sustainability Report: Making a material difference (2020–21). pp. 31–32. <https://www.ultratechcement.com/content/dam/ultratechcementwebsite/pdf/sustainability-reports/ultraTech-cement-sustainability-report-2020-21.pdf>
13. Shree Cement Limited: Corporate sustainability report: Innovative to survive and collaborative to thrive (2019–20). pp. 66–67. <https://www.shreecement.com/uploads/cleanupload/16th-sustainability-report-shree-cement-2019-20.pdf>
14. Dalmia Cement (Bharat) Limited: Investor presentation (2021). [https://www.dalmiacement.com/wp-content/uploads/2021/09/Investor-Presentation\\_September.pdf](https://www.dalmiacement.com/wp-content/uploads/2021/09/Investor-Presentation_September.pdf)
15. Confederation of Indian Industry: Energy benchmarking for Indian cement industry (2019).
16. Murumkar, M.: Challenges While Utilising Hazardous Industrial Waste, pp. 24–27. *Indian cement review*, Mumbai (2020)
17. Ministry of Environment forest and climate change: Government of India: List of processes generating hazardous wastes (2016). pp. 1–68. <http://www.iwma.in/HWM%20Rules.pdf>
18. Deolalkar, S.P.: Chapter 1—general introduction. In: Deolalkar, S.P. (ed.) *Designing Green Cement Plants*, pp. 63–69. Butterworth-Heinemann, Oxford (2016). <https://doi.org/10.1016/B978-0-12-803420-0.00008-1>
19. Ministry of housing and urban affairs Government of India: Guidelines on usage of refuse derived fuel in various industries (2018). pp. 13–14. <http://cpheeo.gov.in/upload/5bda791e5a fb3SBMRDFBook.pdf>
20. Central pollution control board, M.o.E., Forest and Climate Change, Govt. of India: Interim Report of Monitoring Committee on Management of Hazardous Waste (2019). pp. 41–42. <http://www.indiaenvironmentportal.org.in/content/461822/interim-report-of-monitoring-committee-on-management-of-hazardous-waste/>
21. Central pollution control board, M.o.E., Forest and Climate Change, Govt. of India: Annual report 2019–20 on implementation of Plastic Waste Management Rules, 2016. (2019–20). [https://cpcb.nic.in/uploads/plasticwaste/Annual\\_Report\\_2019-20\\_PWM.pdf](https://cpcb.nic.in/uploads/plasticwaste/Annual_Report_2019-20_PWM.pdf)
22. Pasalkar, A.A., Bajaj, Y.M., Wagh, A.A., Dalvi, J.D.: Comprehensive literature review on use of waste tyres rubber in flexible road pavement. *Int. J. Eng. Res. Technol.* (2015). <https://doi.org/10.17577/IJERTV4IS020596>
23. Bharati Chaturvedi, Rajat Rai Handa: Circulating tyres in the economy. *Chintan environmental research and action group* (2017). pp. 16–17. <https://cupdf.com/document/circulating-tyres-in-the-economy-reportfinalpdf-6-7-manufacturers-like-balaji.html>
24. Ministry of new and renewable energy, G.o.I.: Bio energy.: <https://mnre.gov.in/bio-energy/current-status>. Accessed 17 September 2021
25. Council for leather exports, s.b.M.o.C.I., Government of India: footwear industry: best foot forward. <https://leatherindia.org/footwear-industry-best-foot-forward/>. Accessed 12 April 2022
26. United nations industrial development organization: Wastes generated in the leather products industry (2003). pp. 22–23. [https://open.unido.org/api/documents/4788516/download/WASTES%20GENERATED%20IN%20THE%20LEATHER%20PRODUCTION%20INDUSTRY%20\(23438.en](https://open.unido.org/api/documents/4788516/download/WASTES%20GENERATED%20IN%20THE%20LEATHER%20PRODUCTION%20INDUSTRY%20(23438.en)
27. Confederation of Indian Industry: Approach paper for achieving 25% thermal substitution rate in Indian cement industry by 2025 (2016). pp. 1–8. [http://www.ciiwasteexchange.org/doc/annexure\\_6.pdf](http://www.ciiwasteexchange.org/doc/annexure_6.pdf)
28. Verisk Maplecroft: Waste generation and recycling Indices 2019 overview and findings (2019). pp. 5–6. <https://www.maplecroft.com/insights/analysis/us-tops-list-of-countries-fuelling-the-mounting-waste-crisis/>
29. Cembureau The European Cement Association: Activity report. Cembureau (2019). pp. 1–37.
30. Kosajan, V., Wen, Z., Zheng, K., Fei, F., Wang, Z., Tian, H.: Municipal solid waste (MSW) co-processing in cement kiln to relieve China's Msw treatment capacity pressure. *Resour., Conserv. Recycl.* (2021). <https://doi.org/10.1016/j.resconrec.2020.105384>
31. Central pollution control board: *Guidelines for Pre-Processing and Co-Processing of Hazardous and Other Wastes in Cement Plant as per H&OW(M & TBM) Rules, 2016* 2017. p. 1–34
32. Kaaremaa, J.: (2021) Wise about waste. *World Cement*, May ed. 71–74.
33. Abbas, T.: Michalis Akritopoulos, Calciner challenges, in *World cement*. (2018)
34. Karstensen, K.H., Saha, P.K., Vigerust, E., Paulsen, A.A., Engelsens, C. J. Ahmadi, M.: Asia's plastic potential. *International Cement Review*, March ed (2021). <https://www.cemnet.com/Articles/story/168461/asia-s-plastic-potential.html>
35. Saxena, A., Chaturvedi, S., Ojha, P., Agarwal, S., Mittal, A., Sharma, P., Ahamad, G., Mazumdar, R., Arora, V., Kalyani, K., Anupam, Singh, B., Kukreja, K., Ahmed, R., Bohra, A. Kaura, P.: *Compendium The Cement Industry India*. National council for cement and building materials, India. pp. 251–260 (2019)
36. Confederation of Indian industry: status paper on alternate fuel usage in Indian cement industry (2018). pp. 1–2. <http://www.ciiwasteexchange.org/doc/afr2018.pdf>
37. Sharma, P., Sheth, P. Mohapatra, B.N.: Waste to energy: issues, opportunities and challenges for RDF utilization in Indian cement industry. *Proceedings of the 7th International Conference on Advances in Energy Research*. pp. 891–900. Springer, Mumbai (2019). [https://doi.org/10.1007/978-981-15-5955-6\\_84](https://doi.org/10.1007/978-981-15-5955-6_84)
38. Kukreja, K., Anupam, Sharma, P. Bhatnagar, S.: Handling of Multi type Alternative Fuels : A Challenge and Opportunity for Cement Plant in 16th NCB International Seminar on Cement, Concrete and Building Materials. (2019): New Delhi
39. Kukreja, K., Mohapatra, B. N. Saxena, A.: Transfer chute design for solid alternative fuels. *Indian cement review*, May ed. (2019). 52–53.
40. Rajamohan, R., Vinayagamurthi, K., Kumar, R.A.K.: Alternative fuel & raw material: our journey with in-house systems—a glimpse. In: *15th NCB International Seminar on Cement, Concrete and Building Materials* (2017): New Delhi
41. Miskolczi, N., Buyong, F., Williams, P.T.: Thermogravimetric analysis and pyrolysis kinetic study of Malaysian refuse derived fuels. *J. Energy Instit.* **83**, 125–132 (2010). <https://doi.org/10.1179/014426010X12759937396632>
42. Cozzani, V., Petarca, L., Tognotti, L.: Devolatilization and pyrolysis of refuse derived fuels: characterization and kinetic modeling by a thermogravimetric and calorimetric approach. *Fuel* **74**, 903–912 (1995). [https://doi.org/10.1016/0016-2361\(94\)00018-M](https://doi.org/10.1016/0016-2361(94)00018-M)
43. Fang, D., He, F., Xie, J.: Pyrolysis characteristics and mechanism of hydrocarbon compounds for RDF. *Fullerenes, Nanotubes and Carbon Nanostruct.* **29**, 13–20 (2021). <https://doi.org/10.1080/1536383X.2020.1803287>
44. Chen, X., Xie, J., Mei, S., He, F., Yang, H.: RDF pyrolysis by TG-FTIR and Py-GC/MS and combustion in a double furnaces reactor. *J. Therm. Anal. Calorim.* **136**, 893–902 (2019). <https://doi.org/10.1007/s10973-018-7694-9>

45. Kusz, B., Kardaś, D., Heda, Ł., Trawiński, B.: Pyrolysis of RDF and catalytic decomposition of the produced tar in a char bed secondary reactor as an efficient source of syngas. *Processes* **10**, 90 (2022). <https://doi.org/10.3390/pr10010090>
46. Park, S.-W., Seo, Y.-C., Lee, S.-Y., Yang, W.-S., Oh, J.-H., Gu, J.-H.: Development of 8 ton/day gasification process to generate electricity using a gas engine for solid refuse fuel. *Waste Manag.* **113**, 186–196 (2020). <https://doi.org/10.1016/j.wasman.2020.06.004>
47. Ferreira, C.R.N., Infiesta, L.R., Monteiro, V.A.L., Starling, M.C.V.M., da Silva Júnior, W.M., Borges, V.L., Carvalho, S.R., Trovó, A.G.: Gasification of municipal refuse-derived fuel as an alternative to waste disposal: process efficiency and thermochemical analysis. *Process Saf. Environ. Prot.* **149**, 885–893 (2021). <https://doi.org/10.1016/j.psep.2021.03.041>
48. energy, S.c.o.: Power generation from municipal solid waste. (2016). pp. 96
49. IEA.: 100 MT Coal Gasification Target by 2030—Policies.: <https://www.iea.org/policies/12931-100-mt-coal-gasification-target-by-2030>. Accessed 27 Aug 2021
50. India, G.o.: Five Year Vision Document 2019–2024 Group III—Resources.
51. Clark, M.: Impacts of alternative fuels. *International Cement Review*, August edn. 58–59 (2019).
52. Mora, N., Martinez, J. Ayala, C., Clinker production with high chlorine alternative fuels. In 15th International Congress on the Chemistry of Cement: Prague, Czech Republic (2019)
53. Schmidt, D., Abbas, T. Akritopoulos, M.: Modelling 100% AF TSR. *International Cement Review*, September edn. (2019).
54. Mohapatra, B., Chaturvedi, S., Saxena, A., Sharma, P., Bohra, A., Naidu, G.: Use of alternative fuels and raw materials in cement industry in India—prospects & challenges in conserve green & sustainable resources. New Delhi (2019)
55. Kara, M., Günay, E., Tabak, Y., Durgut, U., Yıldız, Ş, Enç, V.: Development of refuse derived fuel for cement factories in Turkey. *Combust. Sci. Technol.* **183**, 203–219 (2010). <https://doi.org/10.1080/00102202.2010.512580>
56. Mohapatra, B.N., Vyas S.K., Shekhar, C.: Indian experience of using AFR in cement kiln. In: *Industrial Angels*. pp. 5–13 (2014)
57. Gautam, S., Jain, R., Mohapatra, B., Joshi, S.Gupta, R.: Energy Recovery from Solid Waste in Cement Rotary Kiln and its Environmental Impact. In: 24th International Conference on Solid Waste Technology & Management: Philadelphia (2009)
58. Rahman, A., Rasul, M.G., Khan, M.M.K., Sharma, S.: Aspen plus based simulation for energy recovery from waste to utilize in cement plant preheater tower. *Energy Procedia* **61**, 922–927 (2014). <https://doi.org/10.1016/j.egypro.2014.11.996>
59. Kara, M.: Environmental and economic advantages associated with the use of RDF in cement kilns. *Resour. Conserv. Recycl.* **68**, 21–28 (2012). <https://doi.org/10.1016/j.resconrec.2012.06.011>
60. Pieper, C., Wirtz, S., Schaefer, S., Scherer, V.: Numerical investigation of the impact of coating layers on RDF combustion and clinker properties in rotary cement kilns. *Fuel* **283**, 1–13 (2021). <https://doi.org/10.1016/j.fuel.2020.118951>
61. El-Salamony, A.-H.R., Mahmoud, H.M., Shehata, N.: Enhancing the efficiency of a cement plant kiln using modified alternative fuel. *Environ. Nanotechnol. Monit. Manag.* **14**, 100310 (2020). <https://doi.org/10.1016/j.enmm.2020.100310>
62. Alsop, P.: *The cement plant operations handbook*. Warners (Midlands) Plc, UK (2019)
63. Lin, S., Kiga, T., Wang, Y., Nakayama, K.: Energy analysis of CaCO<sub>3</sub> calcination with CO<sub>2</sub> capture. *Energy Procedia* **4**, 356–361 (2011). <https://doi.org/10.1016/j.egypro.2011.01.062>
64. Qiao, J., Chai, T.: Soft measurement model and its application in raw meal calcination process. *J. Process Control* **22**, 344–351 (2012). <https://doi.org/10.1016/j.jprocont.2011.08.005>
65. A/S, F.L.: Low NO<sub>x</sub> calciner.: <https://search.ebscohost.com/login.aspx?direct=true&db=edsprg&AN=edsprg.10974992&site=eds-live&scope=site>. Accessed 25 September 2021
66. Keefe, B.P., Shenk, R.E.: Staged combustion for low-NO<sub>x</sub> calciners. In: *Cement Industry Technical Conference*, pp. 255–264. IEEE, Jacksonville, FL, USA (2002). <https://doi.org/10.1109/2002.1006511>
67. FLSmidth: Efficient alternative fuel combustion device.: <https://www.flsmidth.com/en-gb/products/pyro/hotdisc-combustion-device>. Accessed 15 Sep 2021
68. das, A.: Prepol® Step combustor—a flexible solution for low quality alternative fuels, Thyssenkrupp (2020)
69. Mersmann, M. Schmitgen, S.: Versatile AF burning. *International cement review*, May ed. (2021) <https://www.cemnet.com/Articles/story/170758/versatile-af-burning.html>.
70. Tokheim, L.-A., Mathisen, A., Øi, L.E., Jayarathna, C.K., Eldrup, N.H., Gautestad, T.: Combined calcination and CO<sub>2</sub> capture in cement clinker production by use of electrical energy. In: *Trondheim CCS Conference—CO<sub>2</sub> Capture Transport and Storage*. SINTEF Academic Press, Norway (2019)
71. Mathisen, A., Skinnemoen, M. Nord, L.: Evaluating CO<sub>2</sub> capture technologies for retrofit in cement plant. In: 12th International Conference on Greenhouse Gas Control Technologies, GHGT-12, Austin, Texas (2014). <https://doi.org/10.1016/j.egypro.2014.11.684>.
72. Gerbelová, H., van der Spek, M., Schakel, W.: Feasibility assessment of Co<sub>2</sub> capture retrofitted to an existing cement plant: post-combustion vs oxy-fuel combustion technology. *Energy Procedia* **114**, 6141–6149 (2017). <https://doi.org/10.1016/j.egypro.2017.03.1751>
73. Nhuchhen, D.R., Sit, S.P., Layzell, D.B.: Alternative fuels co-fired with natural gas in the pre-calciner of a cement plant: energy and material flows. *Fuel* **295**, 1–16 (2021). <https://doi.org/10.1016/j.fuel.2021.120544>
74. Jacek Wydrych Dobrowolski, B.: Numerical Calculations of limestone calcination in cement industry with use of shrink core model. In: *AIP Conference Proceedings 2078* (2019). <https://doi.org/10.1063/1.5092037>.
75. Mikulčić, H., von Berg, E., Vujanovic, M., Priesching, P., Tatschl, R., Duic, N.: Numerical analysis of cement calciner fuel efficiency and pollutant emissions. *Clean Technol. Environ. Policy* (2013). <https://doi.org/10.1007/s10098-013-0607-5>
76. Wang, X., Mikulčić, H., Dai, G., Zhang, J., Tan, H., Vujanović, M.: Decrease of high-carbon-ash landfilling by its co-firing inside a cement calciner. *J. Cleaner Prod.* **293**, 1–11 (2021). <https://doi.org/10.1016/j.jclepro.2021.126090>
77. Nakhaei, M., Grévaïn, D., Jensen, L.S., Glarborg, P., Dam-Johansen, K., Wu, H.: NO emission from cement calciners firing coal and petcoke: a CPFED study. *Appl. Energy Combust. Sci.* **5**, 1–13 (2021). <https://doi.org/10.1016/j.jaecs.2021.100023>
78. Cristea, E.-D. Conti, P.: Numerical investigation on multiphase reacting/combusting turbulent flows: aerodynamics, kinetics, heat and mass transfer inside a cement kiln precalciner. In: *ASME-JSME-KSME 2019 8th Joint Fluids Engineering Conference*. (2019), ASME: San Francisco, California, USA. <https://doi.org/10.1115/AJKFluids2019-5033>.
79. Rodríguez Gómez, N., Alonso, M., Grasa, G., Abanades, J.: Heat requirements in a calciner of CaCO<sub>3</sub> integrated in a CO<sub>2</sub> capture system using CaO. *Chem. Eng. J.* **138**, 148–154 (2008). <https://doi.org/10.1016/j.cej.2007.06.005>
80. Mikulčić, H., von Berg, E., Vujanović, M., Priesching, P., Perković, L., Tatschl, R., Duić, N.: Numerical modelling of calcination reaction mechanism for cement production. *Chem. Eng. Sci.* **69**, 607–615 (2012). <https://doi.org/10.1016/j.ces.2011.11.024>
81. Dou, H., Chen, Z. Huang, J.: Numerical study of the coupled flow field in a double-spray calciner. In: *International Conference*

- on Computer Modeling and Simulation. (2009). Macau, China: IEEE. <https://doi.org/10.1109/ICCMS.2009.45>.
82. Qiao, J., Zhao, X., Chai, T.: Soft Measurement Model of Raw Meal Decomposition Ratio Based on Data Driven for Raw Meal Calcination Process. In: Chinese Control Conference (CCC). (2019). Guangzhou, China: IEEE. <https://doi.org/10.23919/ChiCC.2019.8866598>.
  83. Zhang, Y., Cao, S.-X., Shao, S., Chen, Y., Liu, S.-L., Zhang, S.-S.: Aspen Plus-based simulation of a cement calciner and optimization analysis of air pollutants emission. *Clean Technol. Environ. Policy* **13**, 459–468 (2011). <https://doi.org/10.1007/s10098-010-0328-y>
  84. Akhtar, S.S., Abbas, T., Goetz, J., Kandamby, N. A Calciner at its Best. In: IAS/PCA cement industry conference (2019). St. Louis, MO, USA: IEEE. <https://doi.org/10.1109/CITCON.2019.8729114>.
  85. Mone, S., Gawali, B.S., Joshi, M. S. Vitankar, V.: Detailed CFD model for predicting combustion, calcination and pollutant formation in calciner, in 16th NCB International Seminar on Cement, Concrete and Building Materials: New Delhi (2019)
  86. Jianxiang, Z., Yan, W., Xiuli, Z.: Hydrodynamic Modelling of Gas and Solid Flows in the Pre- Calciner. In: Asia-Pacific Power and Energy Engineering Conference. (2012). Shanghai, China: IEEE. <https://doi.org/10.1109/APPEEC.2012.6307057>.
  87. Speer, U. Keiser, A.: High efficiency SNCR control system with online—CFD and NOx prediction for the cement industry. In: IAS/PCA Cement Industry Technical Conference. (2017). Calgary, AB, Canada: IEEE. <https://doi.org/10.1109/CITCON.2017.7951853>.
  88. Nance, G., Abbas, T., Lowes, T., Bretz, J.: Calciner design for lower CO and NOx using MI-CFD analysis to optimize “Hot-Reburn” Conditions. In: IAS/PCA 53rd Cement Industry Technical Conference. (2011). St. Louis, MO, USA: IEEE. <https://doi.org/10.1109/CITCON.2011.5934552>.
  89. Abbas, T., Akritopoulos, M. Akhtar, S.S.: Reducing pressure drop in pyro-processing. In: IAS/PCA Cement Industry Conference. (2018). Nashville, TN, USA: IEEE. <https://doi.org/10.1109/CITCON.2018.8373111>.
  90. Abbas, T., Bretz, J., Garcia, F. Fu, J.: SO<sub>2</sub>, CO and NO analysis of a SL calciner using a MI-CFD model. In: IAS/PCA Cement Industry Conference. (2015). Toronto, ON, Canada: IEEE. <https://doi.org/10.1109/CITCON.2015.7122597>.
  91. ZhuGang, Y. Hui, L.: Soft sensor for apparent degree of calcination in NSP cement production line. In: The 2<sup>nd</sup> International Conference on Computer and Automation Engineering (ICCAE), Singapore: IEEE. (2010). <https://doi.org/10.1109/ICCAE.2010.5451912>.
  92. Zhe, S., Zhugang, Y., Qiang, Z., Xianlei, Z., Dezhi, X.: Sliding mode control for calciner outlet temperature via regression modeling. In: The 27th Chinese Control and Decision Conference (CCDC). (2015). Qingdao, China: IEEE. <https://doi.org/10.1109/CCDC.2015.7162761>.
  93. Yu, H., Wang, F., Wang, X., Ma, X.: Study on dynamic models of cement calciner based on typical working conditions. In: 2016 35th Chinese Control Conference (CCC). (2016). Chengdu, China: IEEE. <https://doi.org/10.1109/ChiCC.2016.7553677>.
  94. Lin, X., Yang, B., Cao, D.: Multi-Parameter Control for Precalciner Kiln System of Cement Using Adaptive Dynamic Programming. In: 2009 International Workshop on Intelligent Systems and Applications. (2009). IEEE. <https://doi.org/10.1109/IWISA.2009.5072967>.
  95. Yu, H., Liu, W., Dong, H.: Research on recognition of working condition for calciner and grate cooler based on expert system. In: 12<sup>th</sup> International Conference on Control Automation Robotics & Vision (ICARCV). (2012). Guangzhou, China: IEEE. <https://doi.org/10.1109/ICARCV.2012.6485411>.
  96. Su, Z., Yuan, Z., Zhang, Q., Zhang, X.: An online switching modeling for calciner outlet temperature via grey correlation analysis. In: International Conference on Information and Automation (ICIA). (2014). Hailar, China: IEEE. <https://doi.org/10.1109/ICInfA.2014.6932705>.
  97. Qiao, J., Tian, F.: Abnormal Condition Detection Integrated with Kullback Leibler Divergence and Relative Importance Function for Cement Raw Meal Calcination Process. In: 2nd International Conference on Industrial Artificial Intelligence (IAI). (2020). Shenyang, China: IEEE. <https://doi.org/10.1109/IAI50351.2020.9262170>.
  98. Zhang, M., Yan, H., Yu, L.: Adaptive Multi-dimensional Taylor Network Control for Cement Calciner Outlet Temperature. In: 4th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC). (2020). IEEE. <https://doi.org/10.1109/ITNEC48623.2020.9084964>.
  99. Zheng, J., Du, W., Lang, Z., Qian, F.: Modeling and optimization of the cement calcination process for reducing NOx emission using an improved just-in-time Gaussian mixture regression. *Ind. Eng. Chem. Res.* **59**, 4987–4999 (2020). <https://doi.org/10.1021/acs.iecr.9b05207>
  100. Cai, Y.: Modeling for the calcination process of industry rotary kiln using ANFIS coupled with a novel hybrid clustering algorithm. *Math. Probl. Eng.* (2017). <https://doi.org/10.1155/2017/1067351>
  101. Baier, H.: Menzel, K. Potentials of AFR co-processing. In: 2011 IEEE-IAS/PCA 53rd Cement Industry Technical Conference. (2011). St. Louis, MO, USA: IEEE. <https://doi.org/10.1109/CITCON.2011.5934550>.
  102. Bapat, J.: Advanced fuel burning technologies in cement production. *Indian Cement Review* **30**(6), 44–46 (2016)
  103. Unitherm Cemcon: M.A.S Kiln Burner. <https://www.unitherm.at/en/products/mas-kiln-burner>. Accessed 26 Aug 2021
  104. D’Hubert, X.: Latest burner profiles. *Global cement magazine* (2017). 10–18. <https://www.globalcement.com/magazine/articles/1018-latest-burner-profiles>.
  105. Cunningham, R.: Swirlax burner conversion leads to 100% petroleum coke firing, in *World cement*. (1998)
  106. Lockwood, F.C. Ou, J. J.: Review: Burning refuse derived fuel in a rotary cement kiln. In: Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. (1993). IMECHE. [https://doi.org/10.1243/PIME\\_PROC\\_1993\\_207\\_008\\_02](https://doi.org/10.1243/PIME_PROC_1993_207_008_02).
  107. Concrete, M.U.: World first UK hydrogen trials demonstrate pathway to net zero cement. <https://mineralproducts.org/News-CEO-Blog/2021/release31.aspx>. Accessed 8 Oct 2021
  108. Liedmann, B., Wirtz, S., Scherer, V., Krüger, B.: Numerical study on the influence of operational settings on refuse derived fuel co-firing in cement rotary kilns. *Energy Procedia* **120**, 254–261 (2017). <https://doi.org/10.1016/j.egypro.2017.07.176>
  109. Haas, J., Weber, R.: Co-firing of refuse derived fuels with coals in cement kilns: combustion conditions for stable sintering. *J. Energy Instit.* **83**, 225–234 (2010). <https://doi.org/10.1179/014426010X12839334040898>
  110. Pieper, C., Liedmann, B., Wirtz, S., Scherer, V., Bodendiek, N., Schaefer, S.: Interaction of the combustion of refuse derived fuel with the clinker bed in rotary cement kilns: a numerical study. *Fuel* **266**, 138–144 (2020). <https://doi.org/10.1016/j.fuel.2020.117048>
  111. Alternate fuels and raw materials in cement industry: In: 3rd International Conference on Alternate Fuels and Raw materials in the cement industry. (2017). pp. 24–25
  112. Patra, T.K., Mukherjee, S., Sheth, P.N.: Process simulation of hydrogen rich gas production from producer gas using HTS catalysis. *Energy* **173**, 1130–1140 (2019). <https://doi.org/10.1016/j.energy.2019.02.136>

113. Basu, P.: Biomass Gasification, Pyrolysis, and Torrefaction Practical Design and Theory. Elsevier Inc, Amsterdam (2013). <https://doi.org/10.1016/C2011-0-07564-6>
114. Lopez, G., Artetxe, M., Amutio, M., Alvarez, J., Bilbao, J., Olazar, M.: Recent advances in the gasification of waste plastics. A critical overview. *Renew. Sustain. Energy Rev.* **82**, 576–596 (2018). <https://doi.org/10.1016/j.rser.2017.09.032>
115. Susastriawan, A.A.P., Saptoadi, H.: Small-scale downdraft gasifiers for biomass gasification: a review. *Renew. Sustain. Energy Rev.* **76**, 989–1003 (2017). <https://doi.org/10.1016/j.rser.2017.03.112>
116. Ramalingam, S., Rajendiran, B., Subramian, S.: Recent advances in the performance of Co-Current gasification technology: a review. *Int. J. Hydrog. Energy* **45**, 230–262 (2020). <https://doi.org/10.1016/j.ijhydene.2019.10.185>
117. Cencere Eastern Illinois University: Biomass Gasification Research. (2014)
118. Silva, I.P., Lima, R.M.A., Silva, G.F., Ruzene, D.S., Silva, D.P.: Thermodynamic equilibrium model based on stoichiometric method for biomass gasification: a review of model modifications. *Renew. Sustain. Energy Rev.* **114**, 1–22 (2019). <https://doi.org/10.1016/j.rser.2019.109305>
119. Pilar González-Vázquez, M., Rubiera, F., Pevida, C., Pio, D.T., Tarelho, L.A.C.: Thermodynamic analysis of biomass gasification using aspen plus: comparison of stoichiometric and non-stoichiometric models. *Energies* **14**, 181–189 (2021). <https://doi.org/10.3390/en14010189>
120. Patra, T., Nimisha, K.R., Sheth, P.: A comprehensive dynamic model for downdraft gasifier using heat and mass transport coupled with reaction kinetics. *Energy* **116**, 1230–1242 (2016). <https://doi.org/10.1016/j.energy.2016.10.036>
121. Patra, T.K., Sheth, P.N.: Biomass gasification models for downdraft gasifier: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **50**, 583–593 (2015). <https://doi.org/10.1016/j.rser.2015.05.012>
122. Yang, Y., Liew, R.K., Tamothran, A.M., Foong, S.Y., Yek, P.N.Y., Chia, P.W., Van Tran, T., Peng, W., Lam, S.S.: Gasification of refuse-derived fuel from municipal solid waste for energy production: a review. *Environ. Chem. Lett.* **19**, 2127–2140 (2021). <https://doi.org/10.1007/s10311-020-01177-5>
123. Seo, Y.-C., Alam, M. T. Yang, W.-S.: Gasification of municipal solid waste. Gasification for low-grade feedstock. pp. 115–141 (2018). <https://doi.org/10.5772/intechopen.73685>
124. Rao, M.S., Singh, S.P., Sodha, M.S., Dubey, A.K., Shyam, M.: Stoichiometric, mass, energy and exergy balance analysis of countercurrent fixed-bed gasification of post-consumer residues. *Biomass and Bioenergy* **27**, 155–171 (2004). <https://doi.org/10.1016/j.biombioe.2003.11.003>
125. Khosasaeng, T., Suntivarakorn, R.: Effect of equivalence ratio on an efficiency of single throat downdraft gasifier using RDF from municipal solid waste. *Energy Procedia* **138**, 784–788 (2017). <https://doi.org/10.1016/j.egypro.2017.10.066>
126. Molino, A.J., Iovane, P., Donatelli, A., Braccio, G., Chianese, S., Musmarra, D.: Steam gasification of refuse-derived fuel in a rotary kiln pilot plant: experimental tests. *Chem. Eng. Trans.* **32**, 337–342 (2013)
127. Sierra Energy: Powering communities with trash. <https://sierraenergy.com/>. Accessed 5 Oct 2021
128. Pio, D.T., Tarelho, L.A.C., Tavares, A.M.A., Matos, M.A.A., Silva, V.: Co-gasification of refused derived fuel and biomass in a pilot-scale bubbling fluidized bed reactor. *Energy Convers. Manag.* **206**, 21–29 (2020). <https://doi.org/10.1016/j.enconman.2020.112476>
129. Burra, K.G., Gupta, A.K.: Synergistic effects in steam gasification of combined biomass and plastic waste mixtures. *Appl. Energy* **211**, 230–236 (2018). <https://doi.org/10.1016/j.apenergy.2017.10.130>
130. Galvagno, S., Casu, S., Casciaro, G., Martino, M., Russo, A., Portofino, S.: Steam gasification of refuse-derived fuel (RDF): influence of process temperature on yield and product composition. *Energy & Fuels* **20**, 2284–2288 (2006). <https://doi.org/10.1021/ef060239m>
131. IEA Bioenergy: The past, present and future for biomass gasification. In: The IEA Bioenergy Webinar Series (2020).
132. Chatterjee, A., Sui, T.: Alternative fuels—effects on clinker process and properties. *Cem. Concr. Res.* **123**, 1–19 (2019). <https://doi.org/10.1016/j.cemconres.2019.105777>
133. Wang, C.: Utilization of refuse derived fuel in cement industry—a case study in China. In: School of Energy Systems, pp. 1–56. Lappeenranta University of Technology, Lappeenranta (2017)
134. Greil, C., Hirschfelder, H., Turna, O.: Operational results from gasification of waste material and biomass in fixed bed and circulating fluidised bed gasifiers. In: Conference on Gasification: The Clean Choice for Carbon Management, pp. 1–10. Noordwijk, Netherlands (1999)
135. Pinho, L.F.d., Fabiani, L. F. V. R.: Natalia Bernardi Ghisi Celleghini, A flexible technology to produce gray calcined clays. In: Calcined clays for sustainable concrete. Proceeding of the 3rd international conference on calcined clays for sustainable concrete. (2020), Springer, Singapore. [https://doi.org/10.1007/978-981-15-2806-4\\_20](https://doi.org/10.1007/978-981-15-2806-4_20)
136. Hjuler, K.: Gasification with separate calcination. US Patent 8377198 B2 filed May 12, 2009 and issued Dec 10, 2009. FLS-midwidth A/S, Valby (DK) Denmark. pp. 1–7
137. Guo, W., Li, S., He, C., Zhang, C., Li, D., Li, Q., Wang, K., Li, Z., Xiao, J., Cheng, X., Yang, C., Hayashi, T., Inoue, E., Katahata, T., Katoh, S., Ichitani, N., Hashimoto, A. Toshihiro, J.: Waste-processing apparatus. European Patent EP 2 631 222 A1 filed Oct 20, 2011, and issued August 28, 2013. pp. 1–42
138. Schuermann, H. Feiss, M.: Plant for producing cement clinker with gasification reactor for difficult fuels. US Patent 2016/0046525A1 filed Apr 4, 2014 and issued Oct 5, 2015. KHD Humboldt Wedag GmbH, Koeln (DE). pp. 1–6
139. Weil, S., Hamel, S., Krumm, W.: Hydrogen energy from coupled waste gasification and cement production—a thermochemical concept study. *Int. J. Hydrog. Energy* **31**, 1674–1689 (2006). <https://doi.org/10.1016/j.ijhydene.2005.12.015>
140. Streit, N. Feiss, M., Pyro-processing. In: World cement. (2020), Palladian Publications Ltd, England, pp. 30–34
141. European cement research academy GmbH: Carbon capture technology - Options and potentials for the cement industry (2007). pp. 1–96. [https://www.vdz-online.de/fileadmin/redaktion/files/pdf/ECRA\\_Technical\\_Report\\_CCS\\_Phase\\_I.pdf](https://www.vdz-online.de/fileadmin/redaktion/files/pdf/ECRA_Technical_Report_CCS_Phase_I.pdf)
142. Mineral Products Association, Cinar Ltd GmBH, V.: Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility (2019).
143. Talebi, G., Goethem, M.W.M.V.: Synthesis gas from waste plasma gasification for fueling lime kiln. *Ital. Assoc. Chem. Eng.* **37**, 1–6 (2014)
144. Hue, F., Pasquier, M., Pasquier, M.Lac, P.: Cement clinker manufacturing plant. US Patent 9321684 B2 filed Oct 27, 2011, and issued April 26, 2016. VICAT, Paris la Defense (FR). pp. 1–9
145. Argus media group: India's RIL coke gasifiers aid petrochemical strategy. <https://www.argusmedia.com/en/news/1958372-indias-ril-coke-gasifiers-aid-petrochemical-strategy>. Accessed 11 Sep 2021

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.