International Journal of Research in Agricultural Sciences
Volume 2, Issue 4, ISSN (Online): 2348 – 3997)

Design and Development of a Prototype Laboratory Scale Fecal Sludge Compost Pellet Making Machine

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***Abstract* – Utilization of compost manure has been limited due to challenges relating to handling and transport, consistency of application and availability of specialized mechanized equipment. To overcome some of these challenges, a machine for the pelletization of compost from fecal sludge was designed, fabricated and successfully tested at the Mechanical Engineering Workshop and Laboratory of CSIR Institute of Industrial Research in Ghana. This machine is an extruder type of pellet making equipment with key components made up of a hopper, extruder barrel, die, and cutter. Optimal batch size was 20 kg at which the maximum throughput capacity was 96.6 kg/hr, a pelleting capacity of 88.3 kg/hr at an efficiency of 91.4%. Average cylindrical pellet diameter was 7.6 mm and length of 16.88 mm. The durability of the pellets based on the measured Pellet Durability Index ranged between 85.6 and 92.3 % with an average of 88.7 %. Average bulk density of pellets was 0.91 g/cm^3 compared to that of unpelleted fecal sludge compost which was 0.65 g/cm^3.**

***Keywords* – Design, Compost, Pellets, Machine.**

I. Introduction

Composting may be defined as a managed and controlled process of decomposition and breakdown of organic materials in the warm and humid environment of the activities of bacteria, fungi and other microorganisms. It is a controlled biological process in which succession of microbial populations convert organic material into a biologically stable product referred to as compost which is used as organic fertilizer. Materials for composting are decomposable organics such as agricultural waste, waste from food factories and solid municipal waste from the waste stream.

Compost which is the product of composting is an organic fertilizer credited with a higher nutrient content in comparison to un-composted manure. It is known to be easier to spread and its release of nutrients into the soil is slow with a lower potential to degrade water quality. Compost is less likely to contain weed seeds and has reduced pathogen levels such as; salmonella and *E. coli* and fewer odors when compared to un-composted manure. Organic fertilizers contribute to humus thereby improving soil fertility and eventually influencing crop yield and farmers' income [1]. Traditionally, farmers engage in composting to supply organic fertilizers at the subsistence level to their farms and such organic fertilizer commodity does not pass through the market exchange system. However, in recent years organic fertilizers are produced in commercial quantities by organic fertilizer manufacturing enterprises for farmers' use in crop production [2].

In most parts of the developing world especially in sub-Saharan African states including Ghana, human excreta from all kinds of on-site sanitation systems are disposed of without regard to sanitation challenges. According to [3] as reported by [4], these excreta are dumped in the environment without any appropriate treatment. Reference [5] reported for example that in Accra Ghana, over 90% of all collected excreta are directly discharged into the ocean while, farmers who are keen to use the nutrient rich product resort to informal sludge markets. Many countries use human excreta as a cheap source of nutrient to enrich the soil and Ghana has a history of human excreta use as a source of nutrient in farming especially in the northern parts of the country. Reference [6] reports that the prominence of human excreta in recent times is seen in the peri-urban agriculture sector due to its nutritional content, cheap cost and safety in spite of it being treated as waste. The traditional mode of management of human excreta, nonetheless has been found to be ineffective and a drain on the financial resources of the nation as reported by [7]. One solution to overcoming this challenge was found in composting and numerous studies abound to show that farmers are willing to use compost materials to supplement soil nutrients. The International Water Management Institute (IWMI) in Ghana has gone a step further to develop what is described as a user friendly, nutritionally enriched fortified excreta pellets for use by farmers. Reference [4] described the pelletization process of fecal sludge-based fertilizers.

The successful production of fecal sludge based compost pellets would further encourage the use of fecal sludge as a source of manure for farmers.

Pelleting is a process of forcing and shaping bulk material through a die with specific dimensions of openings and thickness by extrusion.

Reference [8] enumerated some of the benefits of compost pellets as:

- Reducing the conservation space because of densification.
- Suitability for mechanization and compatibility with farmer's implements for implanting or scattering.
- Suitability for residential places due to elimination of dust pollution challenges.
- Higher precision with spreaders and reducing manure consumption.
- Suitability for transporting to long distances.
- Suitable for planters and no need for separate operations.
- Ability of long time conservation.
- Ability of adding chemical materials for increasing the quality of pellets.

Pellet making machines were introduced into agriculture in the twentieth century according to [9] and since then the production and demand of pelleted products has kept increasing. Reference [10] reports that in Europe and North America, 98% or more of all animal feeds are fed in the form of pellets, yet in many African countries, reports of a practically non existent demand for and production of pelleted feeds have been made in the early nineties.

A pelletizer has been described by [11] as consisting of a screw pump similar to a screw press or screw conveyor in which feed is compressed and worked to form a semi-solid mass. The material to be pelletized is forced through a restricted opening called the die at the discharge end of the screw. Reference [12] listed some factors that most influence the nature of the pelletized product. These are:

a. The operating condition of the machine such as the temperature, pressure, diameter of the die aperture and the share rate.

b. The rheological properties of the material such as moisture content, the physical state of the materials and their chemical composition, particularly the amount and type of starches, protein and fats contain therein.

c. Leakage flow, which is similar to pressure flow and is driven by a pressure gradient. This flow occurs in the clearance between the screw flights and the barrel and within any slot in the barrel wall or surfaces. Leakage flow reduces the machine output.

Conventionally, there are two types of designs of machines for making pellets; the diskpelleter design and the extruder design.

A. Diskpelleter Design

The basic structure of any diskpelleter machine includes one or two disks with holes and/or a roller. Material to be pelleted is fed between the disks and/or roller such that as the disk and/or roller turns, the material is forced into the holes and emerges as pellets. Diskpelleters are of three kinds; the roller disk die type, the roller ring disk type and the double disk type. Diskpelleters rarely become blocked with material since the material is ground before being forced through the holes and are most suited for materials with comparatively low moisture contents of between 20% and 30 %. A key disadvantage of diskpelleters is the frequent replacement of component parts that wear out quite easily and also damage to the dies and roller if the material contains very hard and abrasive bodies.

B. Extruder Design

Extruder type of pellet making machines has basically a barrel with an auger or screw which pushes the material forcefully towards one end where the die is mounted. The compressed material passes through the holes of the die and emerges as pellets. Extruder type pellet making machines are easily blocked by foreign materials such as stones and fibres. Nonetheless they have a key advantage in being able to control the processing temperature by adjusting the pressure. Besides, pellets of various shapes and sizes can be made by changing the die. This paper discusses the design, prototype fabrication and laboratory testing of a prototype fecal sludge compost pellet making machine for the production of pellets based on the extruder design concepts.

II. MATERIALS AND METHODS

A. Baseline Tests and information

Fecal sludge compost used in the equipment tests was obtained from International Water Management Institute (IWMI) in Ghana. This material had been milled using a hammer mill and mixing with cassava starch as a binding agent. Tests were also conducted to determine the extrusion force required to produce pellets. This was done by adopting a method employed by [13] on grains. A die with 10 mm perforations and 5 mm thickness was mounted under a cylinder containing the fecal sludge compost. A standard laboratory press was used to determine the extrusion force required to force the compost material through the die with the given specifications in order to produce pellets. The die characteristics which include size of holes and thickness were predetermined based on the desired characteristics of the pellets that would be produced. Given that the pelletizer would be operated on a laboratory scale a theoretical capacity of 100 kg/hr was used as a basis for determining design parameters for capacity.

B. Extrusion Force and Pressure

Extrusion force is the force acting along the screw auger and is derived from the product of extrusion pressure and cross sectional area of barrel bore. Thus

$$F_{ext} = P_{ext}\frac{\pi D_i^2}{4} \quad (1)$$

Where F_{ext} is the extrusion force in Newton, D_i is the internal diameter of the cylinder bore in meters and P_{ext} is the extrusion pressure N/m^2.

The internal pressure within the bore of the cylinder during pelleting was considered as the extrusion pressure. According to [14], the intensity of pressure within the barrel may be obtained from the relationship:

$$P_{ext} = \frac{2t\sigma_c}{D_i} \quad (2)$$

Where

P_{ext} is the extrusion pressure in N/m^2

t is the thickness of the cylinder wall in meters

D_i is the internal diameter of the barrel in meters

σ_c is circumferential stress N/m^2

C. Diameter of screw shaft

In computing the diameter of the screw shaft, the equation based on the maximum shear stress with minimal axial loading was employed. Thus according to [14];

$$D^3 = \frac{16}{\pi\rho_{max}}\sqrt{\{(K_bM_b)^2 + (K_tM_t)^2\}} \quad (3)$$

Where D is the diameter of shaft in meters, ρ_{max} is the permissible stress in N/m^2, K_b is the bending moment shock and fatigue factor, M_b is maximum bending moment in Nm, K_t is torsion moment shock and fatigue factor M_t is maximum torsion moment in Nm

D. Pitch of the screw auger

$$C = \frac{\pi}{4}\left(D_s^2 - d_s^2\right)PNf60 \quad (4)$$

Where C is capacity in m^3/hr, N is speed in rpm, f is material factor, P is pitch in meters D_s is major diameter of screw auger in meters and d_s is the minor diameter of screw auger in meters.

E. Length of Screw Auger

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$$L_{aug} = 3.42\,(r + mL_s)\theta \quad (5)$$

Where L_{aug} length of screw auger in meters, L_s is the shaft length in meters, r is the radius of the screw shaft in meters and m the tangent of the tapering angle in radians and θ is the helix angle in radians

F. Power Requirement

The power of the motor required to drive the equipment according to [15] may be obtained from the relationship

$$P_w = 2\pi NT \quad (6)$$

where P_w is the power in watts, N is the speed of the shaft in radians per second and T is the torque in Nm

The torque on the other hand is may be obtained from the formula

$$T = \tau_{max}\frac{\pi D^3}{16} \quad (7)$$

Where τ_{max} is the permissible stress in N/m^2 and D is the diameter of the shaft in meters

G. Equipment fabrication

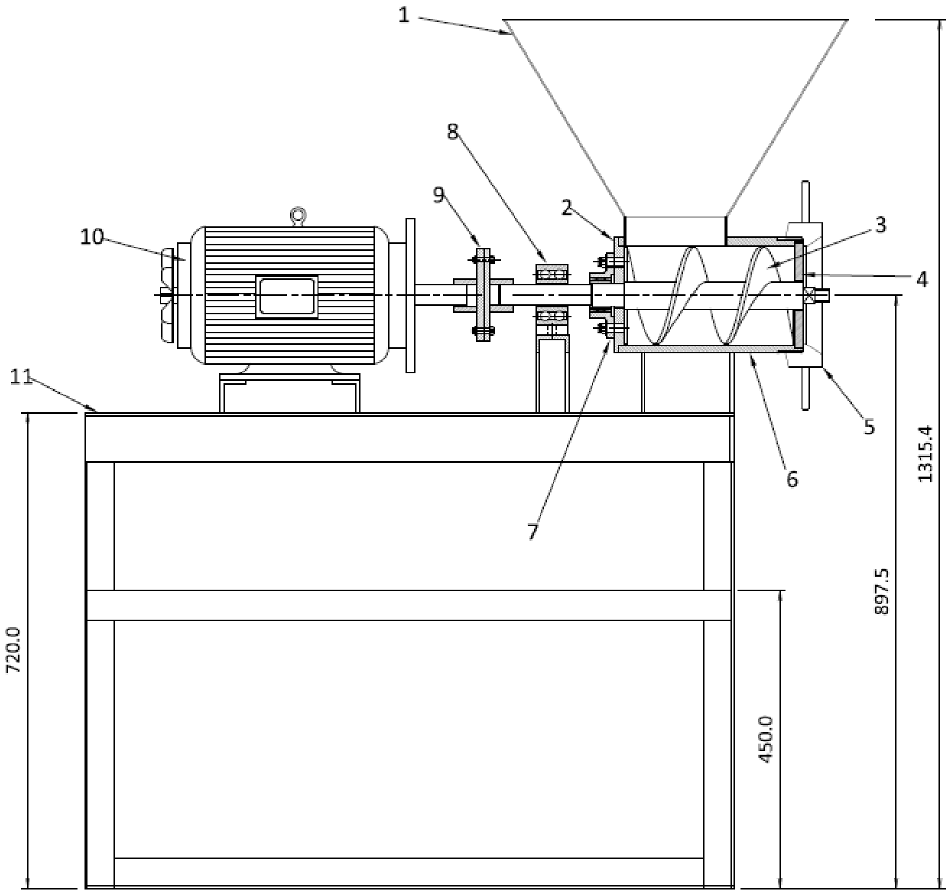
Based on the extruder design concept and the computed theoretical design specifications utilizing necessary equations, standard materials were procured from the local market and the equipment fabricated at the Mechanical Engineering Workshop of CSIR-Institute of Industrial Research in Accra Ghana. Key component parts of the machine include a hopper, a screw auger housed in a cylindrical pelleting chamber with a die mounted at one end. The screw auger and shaft were mounted on pillow bearings and driven by a three phase electric motor

H. Design specifications

Table I shows the design specifications applied to the fabricated equipment.

Table I : Design Specifications of Laboratory Scale Compost Pelletizer

Machine Component	Design Specification
Drive Shaft	Diameter: 70 mm; Length: 550 mm
Screw Auger	Major Diameter: 158.5 mm; Minor Diameter: 70 mm; Length: 450 mm; Pitch: 150 mm; Helix Angle: 15^o; Channel Depth: 45 mm; Screw/Flight Clearance: 1.5 mm; Channel Width: 146 mm; Flight Width: 2.0 mm Screw Rotation Speed: 240 rpm
Cylinder/Barrel	Outside Diameter: 168 mm; Inside Diameter: 160 mm; Thickness: 8 mm; Length: 450 mm
Die	Thickness: 15 mm; Diameter: 162 mm; Diameter of perforations: 8 mm Number of Perforations: 180
Electric Motor	Power: 1.5 kW; Speed: 1440; Reducing Gear ratio: 1:6



1. Hopper **2**. Back Plate **3.** Auger **4.** Die **5.** Cover **6.** Body **7.** Flange Bearing **8.** Pillow Bearing; **9.** Coupling; **10.** Motor; **11** Frame

Fig.1. Sectional View of Pelletizer

I. Performance Evaluation

Performance of the machine was evaluated at two distinct levels: determination of some operational parameters such as capacity and efficiency on the one hand and determination of some characteristics of the pellets produced such as mean diameter, length, durability and bulk density

J. Mode of Operation

Compost material was fed to the machine through the hopper by gravity flow. The screw auger powered by the motor moves the material towards the die end and forces it through the perforations. A rotating knife attached to the shaft where the die is installed cuts the ribbon of pellets that emerge from each hole of the die giving the pellets not only a uniform shape and size but also length.

Fig.2. Prototype pelletizer as fabricated

Fig.3. Pellets produced using the Pelletizer

K. Performance Tests

Fifty pellets were randomly picked from each batch of pellets produced and hot air dried in a batch type hot air drier at drying temperature of 70 ºC for 5 hours. A number of primary parameters of each pellet were determined. These parameters include, dry weight, length, and diameter. Measurements of length and diameter were taken with a digital vernier caliper accurate to 0.01mm while mass was measured using an electronic balance accurate to 0.001 gm. The quality of the pellets was determined on the basis of tests to measure parameters such as durability, and bulk density.

Pellet Durability Index (PDI) was measured to determine the durability of pellets. This parameter is normally used to express the amount of shattering after mechanical or pneumatic shuffling during transport [16]. Standard procedure based on [17] was used. A 100 g sample of the pellet was tumbled at 50 rpm for 10 min in a dust tight enclose. Standard sieve with 3.15 mm apertures were used for the pellets after the tumbling operation. PDI was expressed as the percentage ratio of the mass of pellets retained on the sieve after tumbling to mass of pellet before tumbling. PDI is calculated as the percentage of the weight after assessment from the weight before assessment. According to [18] durability is said to be high when PDI is above 80%, medium when between 70% and 80% and low when below 70%

$$D_U = \frac{M_{pa}\, x 100}{M_{pb}} \quad (8)$$

Where D_u is the percentage durability, M_{pa} mass of pellets retained on the sieve after tumbling in kilograms; M_{pb} mass of pellets retained on the sieve before tumbling in kilograms

Bulk density of the pellet was determined based on procedure recommended by [17]. A container with a volume of 0.5 liter was filled with the pellets and leveled at top surface without compacting the contents of the container and weighed. Bulk density of the pellet was obtained as the ratios of the mass of samples in the container to the volume of the container.

L. Operational parameters

Pelleting Capacity (C_p): This is defined as the mass of pellets produced per batch per unit time and is obtained from the equation

$$C_P = \frac{M_P}{T} \quad (9)$$

Where M_p is mass of pellets and T is the time taken for the mass of pellets to be produced.

Throughput Capacity (T_c): It is the mass of compost material used in the production of pellets per batch per unit time. It is obtained from the formula;

$$T_c = \frac{M_c}{T} \quad (10)$$

Where M_c is the sample mass of compost used to produce the pellets

Pelleting Efficiency (ε_p): It is a measure of how much compost per batch is converted to pellets; using the machine. The following equation is employed.

$$\varepsilon_p = \frac{M_P}{M_c} \quad (11)$$

Bulk Density of Pellets (D_p): The equation employed based on the standard procedure described is

$$D_p = \frac{M_p}{V_p} \quad (12)$$

Where V_p is the sample volume of pellets

III. Results and Discussions

Table I: Some Characteristics of Pellets

Batch No	Mass of compost in 0.5 lit vol Mc50	Bulk Density of compost Bd (g/cm3)	Mass of pellets in 0.5 lit vol Mp50	Bulk Density of pellets Bd (g/cm3)	Mean Diameter of pellets Dp (mm)	Mean Length of pellets Lp (mm)
1	300.28	0.60	425.11	0.85	7.6	14.5
2	295.3	0.59	440.32	0.88	7.5	15.2
3	310.51	0.62	435.40	0.87	7.8	16.8
4	310.22	0.62	450.20	0.90	7.5	17.3
5	310.15	0.62	465.10	0.93	7.5	17.7
6	310.32	0.62	455.80	0.91	7.7	17.5
7	390.1	0.78	475.40	0.95	7.6	17.2
8	330.21	0.66	455.31	0.91	7.7	17.3
9	360.01	0.72	465.42	0.93	7.5	17.8
10	310.12	0.62	460.10	0.92	7.6	17.5
AVG	322.72	0.65	452.82	0.91	7.60	16.88
STDEV	29.85	0.06	15.35	0.03	0.11	1.12

A. Diameter of pellets

The diameter of pellets ranged between 7.5 mm and 7.8 mm with an average of 7.6 mm and a standard deviation of 0.11 for all the ten batches. With die perforations at 8.0 mm, 7.6 mm is an indication of the degree of compactness and densification as a result of the pelleting process.

B. Length of pellets

Pellet length ranged between 14.5 and 17 .8 mm averaging 16.88 mm with a standard deviation of 1.12. The variation may be attributed to inconsistent mixing of the compost materials of different batches. The length also relates to the speed of the knife which is also dependent on the speed of the shaft. The speed of the knife could be made independent of the shaft speed thereby allowing for a variation in the length of pellets without changing the speed of the shaft.

C. Durability

The measured Pellet Durability Index ranged between 85.6 and 92.3 %. The average durability value was 88.7 %. This is considered high and therefore allowing for easy transportation from one location to another without shattering.

D. Bulk density

As expected, the bulk density of unpelleted compost varied between 0.59 g/cm^3 and 0.78 g/cm^3 with a mean of 0.65 g/cm^3 and a standard deviation of 0.06; compared to the bulk density of pellets which ranged between 0.85 g/cm3 and 0.95 g/cm3 and a mean of 0.91 g/cm3 and a standard deviation of 0.03. With a higher bulk density, pelletization meets the key objective of reducing volumes per given mass of compost materials, thereby allowing for larger quantities to be transported per given weight to various locations for utilization. Pelletization is thus a useful and effective method of reducing volumes of compost materials. Savings in volume amounts to 40% on the average.

Table II: Pelletizer Operational Performance data

Batch No	Mass of Compost (Kg)	Pelleting Time (min)	Mass of pellets Produced (Kg)	Throughput Capacity (Kg/hr)	Pelleting Capacity (Kg/hr)	Pelleting Efficiency (%)
1	5.3	3.9	4.5	81.5	69.2	84.9
2	8.5	6.1	7.3	83.6	71.8	85.9
3	11.6	7.9	10.0	88.1	75.9	86.2
4	15.1	9.7	13.8	93.4	85.4	91.4
5	19.8	12.3	18.1	96.6	88.3	91.4
6	24.2	15.3	22.0	94.9	86.3	90.9
7	31.1	19.6	28.2	95.2	86.3	90.7
8	35.4	22.3	32.1	95.2	86.4	90.7
9	42.7	26.9	38.6	95.2	86.1	90.4
10	49.7	32.4	44.8	92.0	83.0	90.1
AVG		15.6	21.9	91.6	81.9	89.3
STD		9.45	13.68	5.33	6.90	2.53

E. Throughput Capacity

Throughput capacity ranged between 81.5 kg/hr and 96.6 kg/hr averaging 91.6 kg/hr with a standard deviation of 5.27 for the ten batches. This compares very favorably with the designed capacity of 100 kg/hr.

F. Pelleting Capacity

This ranged between 69.2 kg/hr to 86.4 kg/hr and a standard deviation of 6.9. The average was 81.9 kg/hr.

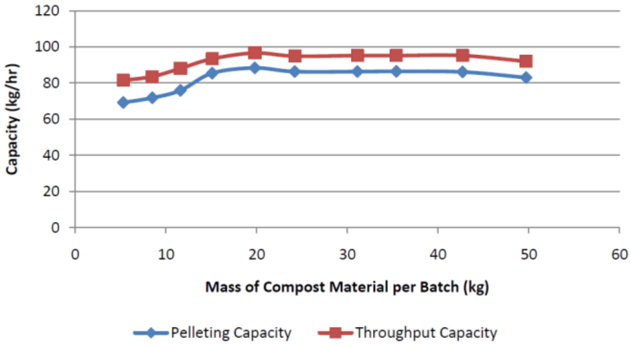


Fig.4. Variation of Mass of Compost Material per Batch with Capacity

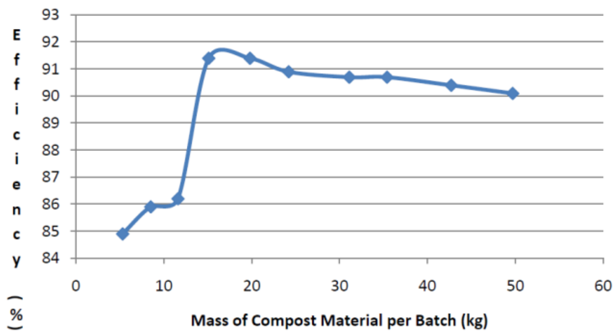


Fig.5. Variation of batch size with efficiency of pelletization

As expected, Fig. 4 showed that pelleting and throughput capacities follow the same trend. The optimal batch size was found to be about 20 kg/hr

G. Pelleting Efficiency

Average pelleting efficiency was 89.3% ranging between 84.9% and 91.4%. Fig. 5 shows the relationship between the quantity of compost fed into the hopper per batch and the efficiency of pelleting. It is deduced from the diagram that the pelletizing operation increases in efficiency up to between 20 and 25 kg per batch and then begins to fall thereafter. It may therefore be concluded that the optimal batch size for efficient pelletizaion is between 20 and 25 kg of compost material

IV. Conclusion

A compost pellet making machine has been successfully designed, fabricated and tested with compost from fecal sludge. Given the characteristics of the compost material used for testing, the optimal batch size for the equipment is 20 kilograms. The actual capacity of 91.6 kg/hr was close to the designed capacity of 100kg/hr, indicating that the design assumptions made were close to reality. Average cylindrical pellet diameter was 7.6 mm and length of 16.88 mm. The Pellet Durability Index ranged between 85.6 and 92.3 % with an average of 88.7 % which indicates that the pellets are good in terms of durability. With an average bulk density of pellets being 0.91 g/cm^3 compared to that of unpelleted fecal sludge compost which was 0.65 g/cm^3, much densification has been achieved through pelletization thereby allowing for larger quantities of compost material to be moved from one site to another. Further investigations are however required to determine the effect of other operational parameters such speed of auger and material characteristics such as moisture content on the operational capacities and efficiencies of the machine.

Acknowledgement

We wish to acknowledge International Water Management Institute IWMI who initiated the project on fecal sludge compost, sponsored the design and fabrication of the equipment as well as provided the material for laboratory testing of the pelletizer.

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