

# Au nanoparticles by instant green chemicals and optimising key synthesis parameters using Taguchi method

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In the recent years, functionalised Au nanoparticles using eco-friendly chemical routes are under the focus for developing several technological applications. However, a simple, reproducible, and controlled synthesis of high-quality nanoparticles is challenging in these approaches. In this work, readily available green chemicals were utilised and the usefulness of and Taguchi approach for optimisation of synthesis procedure was designed for the synthesis of possible lower size Au nanoparticles of size  $93 \pm 7$  nm. L16 orthogonal array, by which the influence of four factors in four levels may well be tested, was chosen. Analysis of variance was done on the attained results and optimum condition suggested by statistical estimations was tested through a verification test. The identified key parameters for synthesising lower size Au nanoparticles are reducing agent (curcumin + cinnamic acid + citric acid), additive (zero), sonication time (30 min), and temperature (50°C) after performing the optimisation technique. Furthermore, this study also provides a selective approach to obtain different shape/size Au nano to colloidal structures through different trail selection within the Taguchi experimental array.

**1. Introduction:** Au nanoparticles (AuNPs) are having potential importance and are in focus with a diverse range of industrial applications in the areas of optics, electronics, catalysis, sensors, medical diagnostics and treatments, antimicrobial agents, coatings, etc [1, 2]. Their prospective significance elicited the development of various cheaper routes of synthesis which vary from chemical to biomolecules assisted approaches for large scale production [2–7]. Although various chemical approaches like seeded growth, supercritical fluid, solvothermal, chemical vapour deposition, and so forth controlling the physical properties of the AuNPs are reported [4, 8, 9]; most of these are still in the developmental stage. In addition, certain problems are often experienced with control of crystal growth, the stability of the nanoparticle preparations and aggregation of the particles [4, 10–12]. In this scenario, bio-based methods as the emerging alternatives are gaining more emphasis as they are eco-friendly, economical, and are suitable for large scale production capabilities [5, 13].

Till date, a broad range of biological systems (live and dead) and biomolecules (including plant molecules) have been used to direct the synthesis of Au nanostructures effectively [5, 13–15]. Within bio-based methodologies, although microbial route syntheses are effective, they have limitations of broad size distributions, hard purification steps, the requirement of proficient personnel, etc [7]. Plant-based methods are user-friendly and have some underpinning advantages like cost-effectiveness, easy separation and purification processes, and so on [2, 7]. The development of green and semi-green techniques for the controlled synthesis of nanoparticles with well-defined size, shape and narrow size distributions became a big challenge and have huge scope [5, 16]. There is an attempt in this area by our group where we employed various plant chemicals and a statistical technique like Taguchi to synthesise smaller Ag and AuNPs [7]. Taguchi approach is simple, robust and can include qualitative and quantitative factors in its procedure and saves the investigation time with multiple parameters inclusion [7, 17].

For prompt applicability of bio-based methodologies, selection of readymade green chemicals (available from both plant and microbial sources) facilitate the process to be simple, convenient, and effective [5, 13–16]. Simultaneous exploitation of mixed chemicals from various sources can outperform the existing techniques

of AuNPs synthesis and can draw new insights. To the best of our knowledge, there is no study till date on the synthesis of AuNPs from readymade green chemicals using a simple Taguchi approach. In this study, we describe a Taguchi approach for the single-step preparation of possible smaller size AuNPs within the selected green chemicals range. Furthermore, this study also introduces an easy approach to attain a bigger size/shape Au nano and colloidal particles from a particular combination of the studied parameters inside Taguchi design.

## 2. Experimental

**2.1. Materials and chemicals:** The chemicals used in this study were purchased from the following companies: cinnamic acid, citric acid from Merck; thiamine, gluconic acid from Molychem; tween 80%, chloroauric acid (HAuCl<sub>4</sub>) which has 49% Au, riboflavin and curcumin from LobaChemie. All chemicals used in this study were of analytical grade and were used as received without additional refinements. Ultrapure water of 18.2 mΩ resistivity was used all through this study.

**2.2. Nanoparticle synthesis, experimental design, and statistical approach:** Similar to our earlier study [4], synthesis of AuNPs, with different parameters, concentrations, and combinations (specified in Table 1) were exposed to HAuCl<sub>4</sub> to obtain nanoparticles. The final strength of HAuCl<sub>4</sub> in each bottle is 0.99 mM with a working volume of 3 ml. The Taguchi approach was used for the optimisation of parameters to synthesise the possible smaller size/shape AuNPs.

Optimisation of four significant parameters such as reducing agent, additive, sonication time, and temperature were studied as shown in Table 1. Investigations were performed using a L16 orthogonal array to produce individual AuNPs (Table 2) at various conditions. Although the colour changes due to AuNPs are quick and spontaneous in many trials, the responses from each trial were analysed after 30 min. The maximum wavelength ( $\lambda_{\max}$ ) of the ultraviolet (UV)–visible spectra due to their surface plasmon resonance (SPR) shifts of each trail is shown in Fig. 1.

Examining the outputs, the verification test was performed to check the optimised conditions and the analysis of variance

**Table 1** Tested parameters along with their studied levels for the synthesis of AuNPs

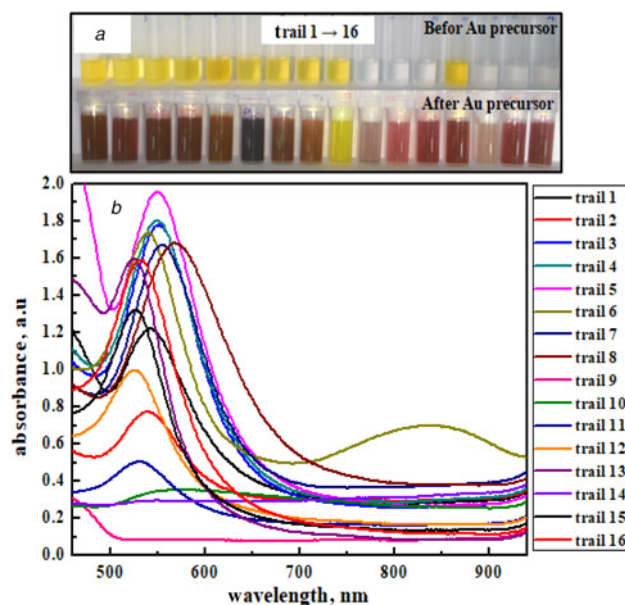
Parameter	Level 1	Level 2	Level 3	Level 4
reducing agent	curcumin (CU) – (9 mM)	curcumin + cinnamic acid + citric acid (CU + CA + CT) – (3 + 3 + 3 mM)	cinnamic acid (CA) – (9 mM)	citric acid (CT) – (9 mM)
additive <sup>a</sup>	riboflavin	thiamine	gluconic acid	none
sonication time, min	0	10	20	30
temperature, °C	30	40	50	60

<sup>a</sup>Each additive's strength is 1 mM and a 10 mM of Tween 80 is also added with each

**Table 2** Levels of the four different factors applied in each one of 16 experimental trails and the observed results in terms of  $\lambda_{\max}$  values (after 2.5 times dilution) in the synthesis of AuNPs

Trail	Reducing agent	Additive	Sonication time, min	Temperature, °C	Results (maximum absorbance values $\lambda_{\max}$ ) of AuNPs
1	CU	Rib	0	30	1.24
2	CU	Thi	10	40	0.75
3	CU	Glu	20	50	1.75
4	CU	zero	30	60	1.82
5	CU + CA + CT	Rib	10	50	1.88
6	CU + CA + CT	Thi	0	60	1.40
7	CU + CA + CT	Glu	30	30	1.70
8	CU + CA + CT	zero	20	40	1.68
9	CA	Rib	20	60	0.18
10	CA	Thi	30	50	0.34
11	CA	Glu	0	40	0.50
12	CA	zero	10	30	0.86
13	CT	Rib	30	40	1.51
14	CT	Thi	20	30	0.34
15	CT	Glu	10	60	1.32
16	CT	zero	0	50	1.64

Glu, gluconic acid; Rib, riboflavin; Thi, thiamine



**Fig. 1** UV-visible spectral analysis of the experimental trails  
*a* Colour changes due to the formation of AuNPs at various L16 experimental trails; left to right in the picture inserts indicate the ascending order (1–16) of the trails  
*b* Spectra with absorption maximum ( $\lambda_{\max}$ ) of each stated trail after 2.5 times dilution

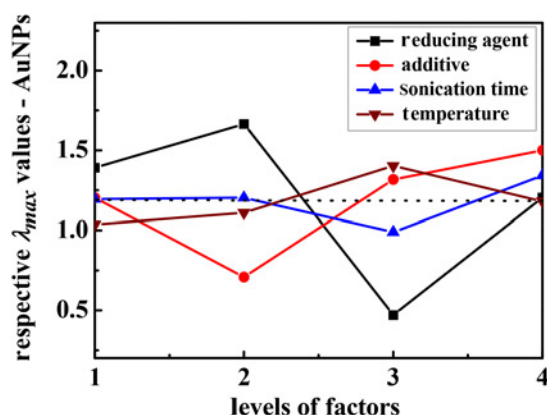
(ANOVA) was performed on the observed results. For the Taguchi array design, ANOVA and the optimisation of the process, Minitab® Release 14, Minitab Inc., USA was used.

**2.3. Analysis and characterisation:** The UV–visible spectra of AuNPs were observed using a spectrophotometer (UV-3600, Shimadzu). The morphology of AuNPs was analysed by scanning electron microscope (SEM, JEOL-2100F) and the X-ray diffraction (XRD) was measured using Philips (PW1830 HT) X-ray diffractometer, in the range of 20–90° (2 $\theta$ ) at a scanning speed of 0.05°/s.

### 3. Results and discussion

**3.1. AuNPs synthesis and Taguchi approach:** In general, wet chemical synthesis procedures of nanostructures are complex in nature and the outputs here majorly depend on more than one parameter [1, 2]. When the required particle size is very small or shape-specific; fine-tuning or control of individual parameters are extremely important. The use of optimisation methodology like Taguchi can help to achieve the possible best procedural or synthesis condition when more than one parameter was changing [8, 9]. Among statistical techniques, the Taguchi methodology may be used quite easily and it has the ability to include categorical factors (e.g. presence or absence of additives) also beside with continuous ones (e.g. temperature, time) [4, 8, 9]. Our earlier study identified the role of additives in Au nanostructures synthesis [4]. So, their presence or absence has been studied as a categorical factor in this study to know its effect on AuNPs synthesis. In addition to the above, reports state that parameters such as reducing agents, capping agents, temperature, sonication, pH, light, metal ion/reducing agent ratio, and so forth played a significant role in tuning size/shape of AuNPs [4, 10, 12]. Thus in this study, the effects of various reducing agents, additives, sonication time, and temperature were studied using an L16 experimental array of Taguchi method (Table 2).

The experimental outcomes for the synthesis of AuNPs in this section are tabulated in Table 2 and the resultant colour changes because of the formation of AuNPs are shown in Fig. 1*a*. The



**Fig. 2** Main effects of factors or average values from the observed results (of respective  $\lambda_{\max}$ ) for AuNPs, wherein each factor is at a given level. For details regarding 'levels', refer to Table 1

**Table 3** ANOVA, stating the 'main effects' of factors for AuNPs

reducing agent	3	3.1359	3.1359	1.04529	14.06	0.028
additive	3	1.3755	1.3755	0.45849	6.17	0.085
sonication	3	0.2548	0.2548	0.08493	1.14	0.458
temperature	3	0.3002	0.3002	0.10007	1.35	0.407
residual error	3	0.2231	0.2231	0.07437	—	—
total	15	5.2894	—	—	—	—

**Table 4** Optimum procedural conditions recommended for the synthesis of AuNPs by statistical estimates after performing the tests

Parameter	AuNPs		
	Level description	Level	$\lambda_{\max}$
reducing agent	CU + CA + CT	2	1.66
additive	zero	4	1.50
sonication time (min)	30	4	1.34
temperature (°C)	50	3	1.40
total contribution of all factors			1.176
current grand average of the performance			1.181
expected result at optimum condition			2.357
experimental value			<b>2.27</b>

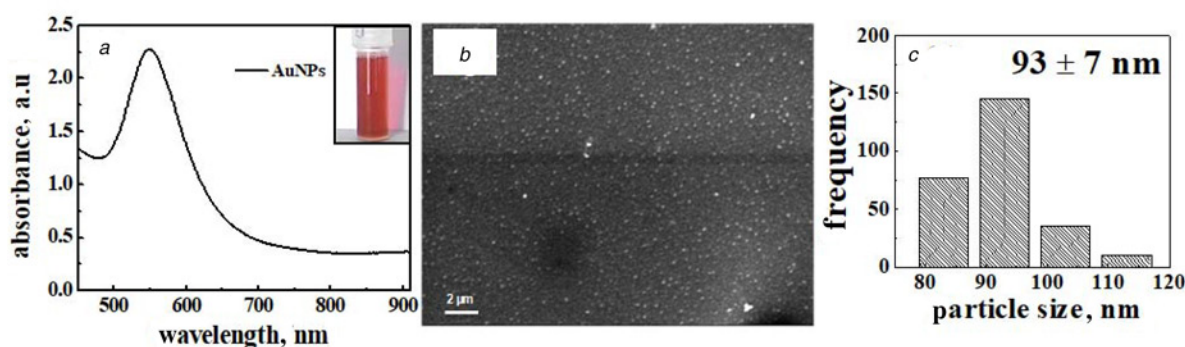
Bold value indicate the achieved value after experimentation.

results are tabulated in terms of the maximum absorption intensity values ( $\lambda_{\max}$ ) through UV–visible spectra due to SPR. The metal nanoparticles, in particular, Au has a strong interaction with light due to the presence of conduction electrons [18]. When the electrons of metal nanoparticles are excited by light of a specific wavelength, they undergo a collective oscillation and this result in SPR [4, 18]. This property can be used to fabricate new generation optical and sensor structures or devices [13] and therefore this study is directed to synthesise AuNPs with high  $\lambda_{\max}$  values. The highest  $\lambda_{\max}$  value of AuNPs was obtained from trail 5 (Table 2) with the following experimental conditions: reducing agent (CU + CA + CT), additive (Rib), sonication time (10 min) and temperature (50°C).

**3.2. Main effects identification and synthesis process optimisation:** Fig. 2 displays the main effect of individual studied factors. The term 'main effect' represents the average value of the observed results (each at its individual  $\lambda_{\max}$ ) in which each factor is at a given level. The dotted line in Fig. 2 indicates the average  $\lambda_{\max}$  value from the obtained 16 experiments of Table 2. ANOVA results for the synthesis of AuNPs shown in Table 3 display that the change in 'reducing agent' of the synthesis medium is the most significant factor (with a  $p$ -value of 0.028, significant at the 0.05  $\alpha$ -level) followed by 'additive' (with a  $p$ -value of 0.085, significant at the 0.10  $\alpha$ -level). The parameters with  $p$ -values > 0.1 from Table 3 indicate the least importance on the synthesis process of individual AuNPs.

After investigating all results, the optimum conditions for having intense SPR active AuNPs are summarised and given in Table 4. From the Table, the estimated SPR absorption intensity is 2.357 for AuNPs and to verify that; a trial was performed using the conditions stated in Table 4. The experimental result of  $\sim 2.27$  at 550 nm (Fig. 3a) is very close to that of the predicted value of 2.357 (Table 4) and the obtained value is  $\sim 1.92$  times more than the value of the maximum average intensity of AuNPs from Table 2. The observed experimental  $\lambda_{\max}$  value at optimum conditions is  $\sim 3.5\%$  less than the predicted value and the difference between the predicted and actual result is minimum (i.e. below 5%) and acceptable.

Fig. 3a shows a colour change of the solution due to AuNPs and its narrow SPR spectral pattern which indicates monodispersity [4, 18]. A typical SEM image showing the size and morphology of the AuNPs is given in Fig. 3b. AuNPs formed are spherical in shape and are homogeneously distributed in the SEM image. The average particle size is given with a distribution plot in Fig. 3c. The size of AuNPs from the SEM image was found to be  $93 \pm 7$  nm with narrow size deviation. The single crystalline



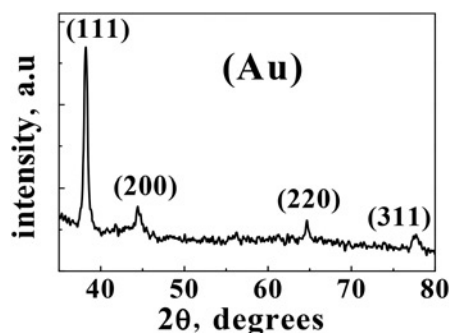
**Fig. 3** Results of AuNPs from optimised parameters

a UV–visible spectra of the AuNPs produced from calculated optimum conditions (Table 4) and upon four times dilution. Figure inset shows the colouration due to AuNPs formation  
b Low magnification SEM images (20,000 $\times$ ) of the as-prepared AuNPs  
c Particle size distribution

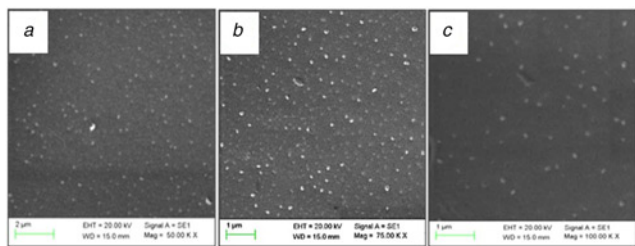


nature of the AuNPs was confirmed by XRD pattern of Fig. 3d. The diffraction pattern with peaks (111), (200), (220), and (311) matches with face centered cubic structure of Au with JCPDS Card No. 04-0784, shows high crystallinity and also matches with other studies as well (Fig. 4) [4, 19]. Additionally, higher magnification images from the same sample (Fig. 3a) are also shown in Fig. 5 for close morphological visualisation and homogenous nature of AuNPs. The images from Figs. 5a–c suggest that the formed AuNPs are homogenous spherical structures throughout. The outcome indicates the suitability of Taguchi approach in directing possible lower size ( $\sim 90$  nm) isotropic AuNPs synthesis.

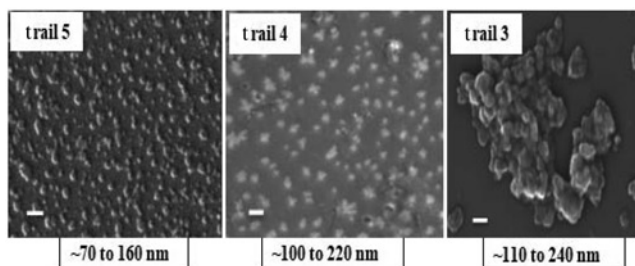
The extinction spectra of nanoparticles with higher  $\lambda_{\max}$  values are important scientifically as it is a direct reflection of its optical property [18, 20]. Furthermore, the light absorption and scattering by nanoparticles are dependent on size, shape, and composition [4, 20]. So, in this study, synthesis conditions where attainment of AuNPs with higher  $\lambda_{\max}$  value is of our primary concern and the optimum process conditions to achieve the same are given in Table 4. Spectra with high  $\lambda_{\max}$  value usually result in lower size particles [4, 18]. However, to validate our approach, the paramount combinations with  $\lambda_{\max}$  values of top three trails (trails 5, 4, 3) from Table 2 are selected and observed for their size and shape patterns microscopically (Fig. 6).



**Fig. 4** XRD analysis of AuNPs obtained from optimum conditions stated in Table 4 and from particles of Fig. 3



**Fig. 5** Higher magnification electron microscopy images of AuNPs from optimised parameters  
a–c Corresponds to additional high magnification SEM images from AuNPs resulted from optimum conditions (Table 1, Fig. 3)



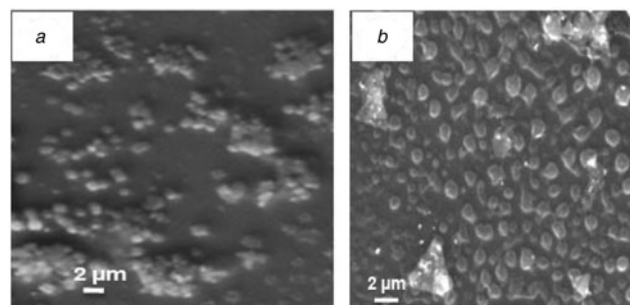
**Fig. 6** SEM images from trails 5, 4, and 3 of Table 2. Scale bar in each figure indicates 0.5  $\mu$ m

Fig. 6 details minimum and maximum size particles from trails 5, 4, and 3 (with  $\lambda_{\max}$  values 1.88, 1.82, and 1.75, from Table 2) which are comparatively higher in size with broader size variations than the AuNPs obtained from the optimum combination (Fig. 3). Therefore, the Taguchi approach of the optimisation is successful in this study by depicting the possible process conditions to achieve possible lower size AuNPs. The unusual spectral properties can also be studied using Taguchi array which reflects particle morphology. For instance, the tail broadening with a decrease of  $\lambda_{\max}$  values results in the increase of size and/or agglomerations in particles [4, 18]. In this study, the atypical spectral pattern was observed by trails 6 and 14 and observations related to them are focused in the later section.

**3.3. Synthesis of anisotropic Au structures:** As mentioned above, the Taguchi approach is useful for designing optimum parameters to synthesise small-sized AuNPs. However, trail 6 and 14 have differed from other studied trails in the overall spectral pattern. Trial 6 displayed two absorption peaks (540 and 840 nm) in contrast to other investigations (Fig. 1b). The studied parameters of trial 6 are; reducing agent (CU + CA + CT), additive (Thi), sonication time (0 min), and temperature (60°C) as mentioned in Table 2. Usually, the absorption of light in the UV–visible region by the metal nanoparticles is due to the SPR phenomenon and is sensitive to the size and shape of the respective nanostructures [4, 18]. In general, the absorption peak in the near-infrared region is because of the presence of non-spherical particles [4]. So, the as-prepared AuNPs were observed under the SEM for detail morphology (Fig. 7).

Fig. 7a shows the nanoparticles obtained from trial 6 are like Au nanosquares with the average size of  $\sim 750$  nm. Stating trail 14, it also differed significantly from other spectral patterns with no intense SPR. SEM images of this sample (Fig. 7b) resulted in bigger triangular, truncated triangular, hexagonal, and near-spherical irregular structures. Bigger structures do not exhibit profound SPR [18] and the same trend is observed in the case of UV–visible spectral analysis for trail 14. Thus, our observations from this study state that Taguchi approach can provide possible lower size AuNPs by trailing with different factors and optimising key synthesis parameters. Moreover, this approach could also be used to get diverse shapes of Au nano to colloidal particle structures as evidenced in this study. ANOVA analysis stated reducing agent (CU + CA + CT) is the key parameter influencing the attainment of lower size AuNPs in this study. Reports state individual CU, CA, and CT has the ability to synthesise and stabilise AuNPs [5, 14, 15] and their combined role and functional groups interplay in guiding size/shape of AuNPs requires further investigation.

There are only a few applications of experimental design for the syntheses of AuNPs have been reported in the literature [7, 16]. An approach like Taguchi design in AuNPs will be useful when



**Fig. 7** SEM images of bigger size AuNPs from  
a From trail 6  
b From trail 14

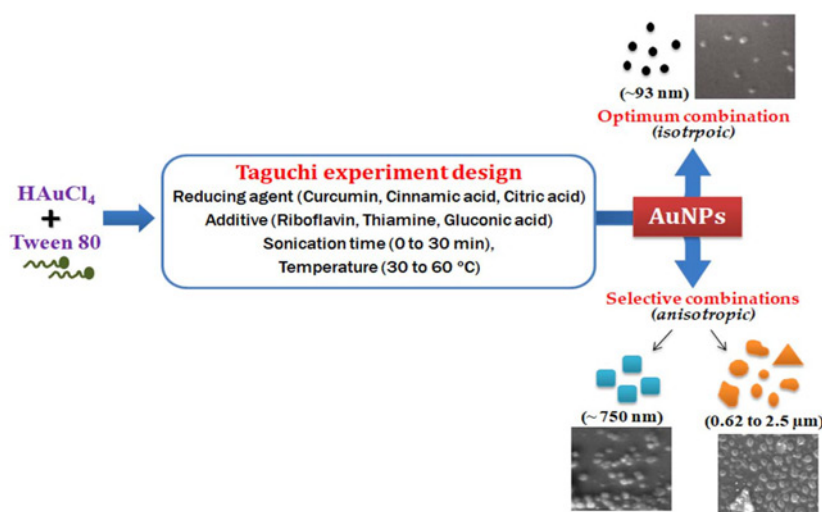


Fig. 8 Taguchi approach used in this study was depicted in a schematic way to synthesise selective size/shape Au nanostructures

there are more parameters qualitative/quantitative are involved and the selection of reaction conditions as a whole often becomes a daunting task [4, 17]. Reports display that the Taguchi analysis was successful in identifying the most influential conditions for AuNPs synthesis within the selected range of parameters. For example, it is 'applied current density' in one study [16], the 'acid amount' in another study [17] and 'temperature' and 'additive' in our earlier attempt with plant extracts [4].

Our group has been working on perfecting the synthesis of AuNPs with narrow size distributions by exploring and utilisation of various instant green chemicals. Thus, in this study, we took the challenge of simple, reproducible, and controlled synthesis of AuNPs with convenient green chemicals. Results indicate 'reducing agent' and 'additive' are the significant parameters affecting the size and AuNPs of possible smaller size  $93 \pm 7 \text{ nm}$  are synthesised using the Taguchi method. This study also shows the possibility to attain Au nano to colloidal particles through different trail selection within the Taguchi multivariate paradigm. The total scheme of this study was given in Fig. 8.

Application of Taguchi approach in biotechnology allied fields have been started and are in practise in various segments like research and development, design of plants, optimisation of processes, quality management, etc [4, 9, 21–23]. Many biotechnological processes and products including novel materials like functionalised organic and/or inorganic nanostructures are highly expected in the market place in the years to come [21, 24]. In this scenario, size and shape control of the nanostructures are extremely important to make novel materials range from sensors to devices. So, this study displayed the size and shape control of AuNPs by successful green route synthesis using readymade biochemicals in a simple, single-step one-pot process, and displayed futuristic scope for attainment of nanoparticles through reduced experimentation. Along with AuNPs, our experimental approach can be extended to produce other mono- and multi-metallic nanostructures which have widespread applications in medical, health care, chemical, remediation, and so forth nanobiotechnological applications [4, 9, 21–23].

**4. Conclusions:** We have developed a convenient synthesis of AuNPs ( $\sim 93 \text{ nm}$ ) by readymade green chemicals using a simple Taguchi approach. The formed AuNPs are spherical, mono-dispersed, homogeneously distributed and exhibited high crystallinity. Optimum synthesis conditions are observed to be as follows: reducing agent (CU + CA + CT), additive (zero), sonication time (30 min), and temperature ( $50^\circ\text{C}$ ) and ANOVA analysis

displayed factors like 'reducing agent' and 'additive' are statistically significant during the synthesis process. Apart from uniform smaller size and distribution control, Taguchi multivariate paradigm in this study facilitated to attain Au nano to colloidal particles with different trail selections (trials 6 and 14). The synthesis concept detailed in this study could ultimately save time and chemicals with limited experimentation and can be widely used to attain different organic and inorganic nanoparticles in a greener way.

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